Halo scraping and collimation of high-intensity hadron beams with hollow electron lenses

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Fermilab

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- Introduction
- Electron lenses and their applications
- Hollow electron beam collimation
- New accelerator research facilities at Fermilab
- Conclusions

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Context and motivation

- **Hollow electron lenses** can be used for **collimation and scraping** of high-power hadron beams when radiation damage and impedance limit the use of conventional collimators
  - Shiltsev, BEAM06, CERN-2007-002
  - Shiltsev et al., EPAC08
- Concept **demonstrated experimentally** at the Fermilab Tevatron collider
  - Measured halo removal rates, effects on the core, enhancement of diffusion, mitigation of loss transients from beam jitter and tune adjustments, ...
    - Stancari, Valishev, et al., Phys. Rev. Lett. **107**, 084802 (2011)
    - Stancari, APS/DPF Proc., arXiv:1110.0144 [physics.acc-ph] (2011)
- Promising technique for the LHC upgrades
  - Design report in preparation

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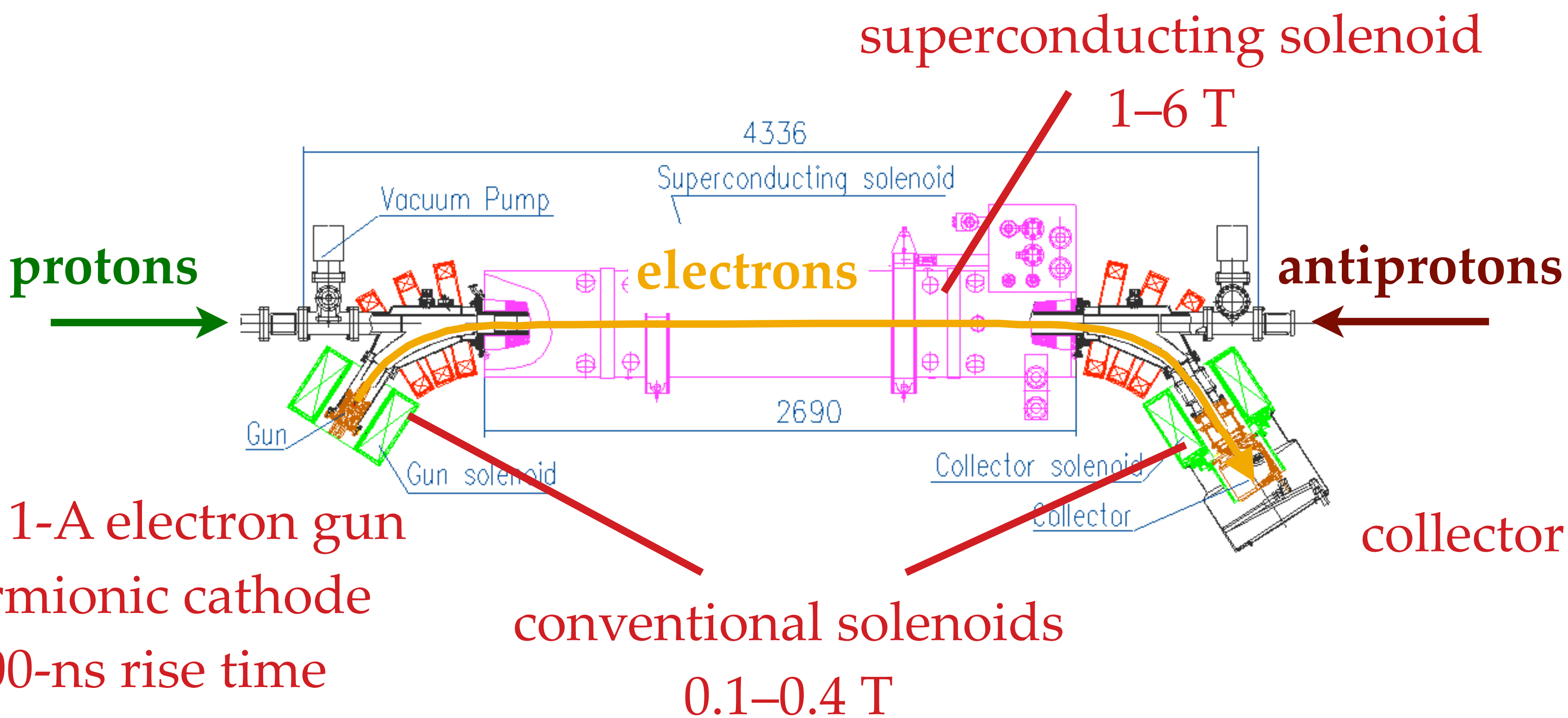
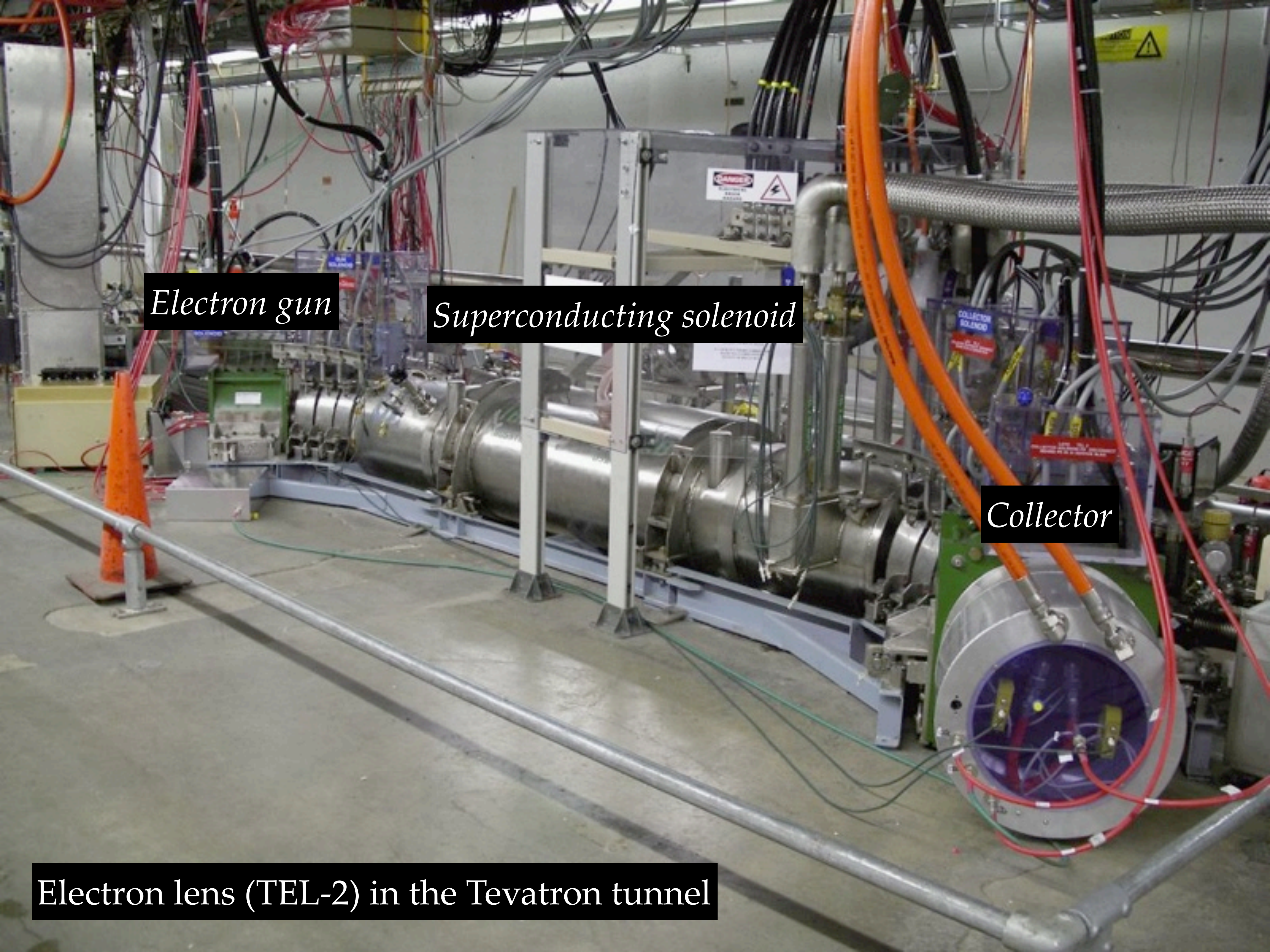
Tevatron electron lenses (TEL)

Proposed in 1990s for use in colliders
Based on electromagnetic field generated by electron beam
Stability provided by strong axial magnetic fields

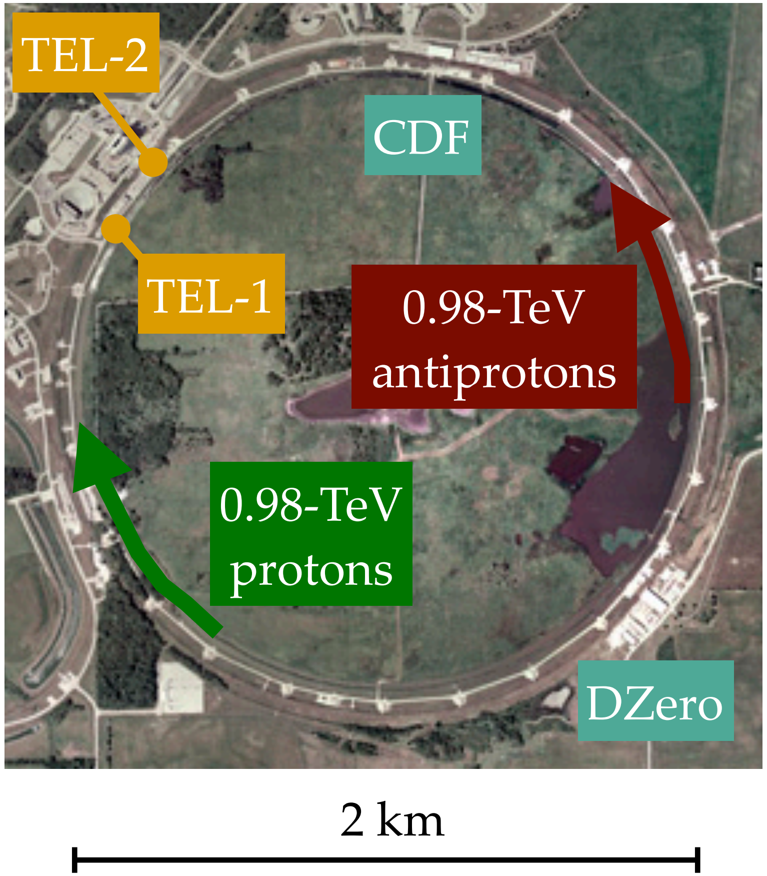


Shiltsev et al., Phys. Rev. ST Accel. Beams **2**, 071001 (1999)
Shiltsev et al., Phys. Rev. Lett. **99**, 244801 (2007)
Shiltsev et al., Phys. Rev. ST Accel. Beams **11**, 103501 (2008)
Shiltsev et al., New J. Phys. **10**, 043042 (2008)


Electron gun
Superconducting solenoid
Collector
Electron lens (TEL-2) in the Tevatron tunnel

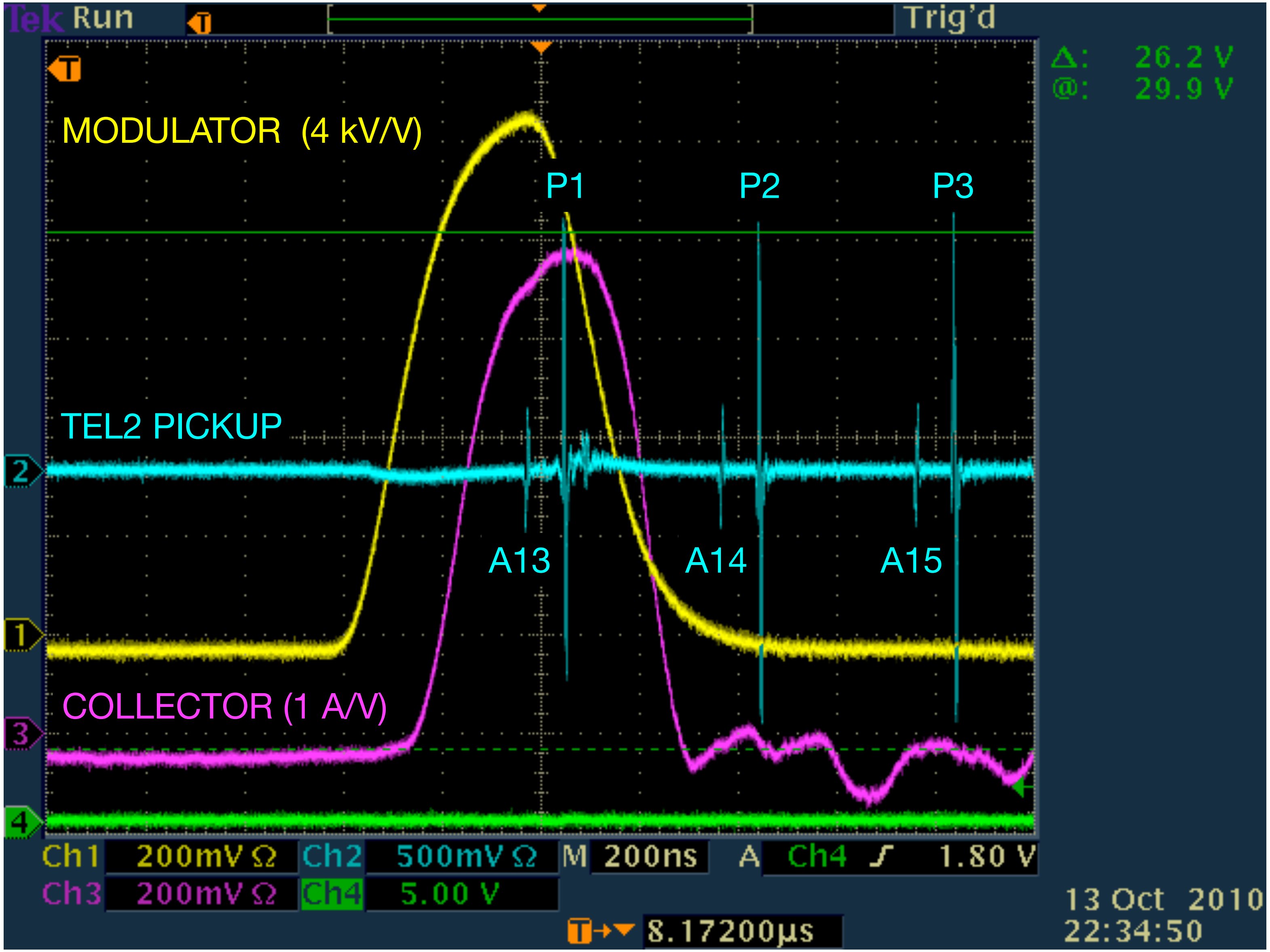
Electron lenses in the Fermilab Tevatron collider

- ***long-range beam-beam compensation***
  - Shiltsev et al., Phys. Rev. Lett. **99**, 244801 (2007)
- ***abort-gap cleaning during operations***
  - Zhang et al., Phys. Rev. ST Accel. Beams **11**, 051002 (2008)
- ***studies of head-on beam-beam compensation***
  - Stancari and Valishev, FERMILAB-CONF-13-046-APC
- ***collimation with hollow electron beams***
  - Stancari et al., Phys. Rev. Lett. **107**, 084802 (2011)



Electron lenses for beam-beam compensation are currently being commissioned in the Relativistic Heavy Ion Collider at Brookhaven National Laboratory

Pulsed operation of the electron lens

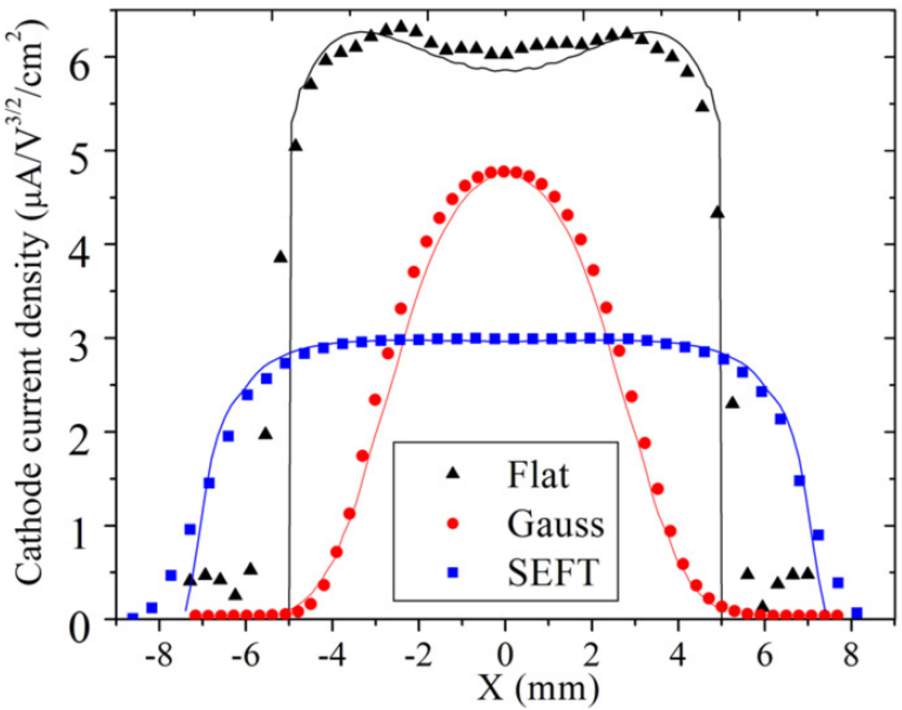


Pulsed electron beam could be **synchronized** with any group of bunches

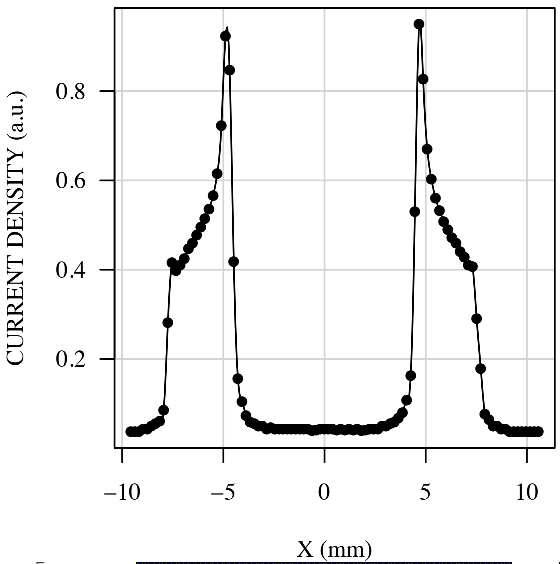
Profile control

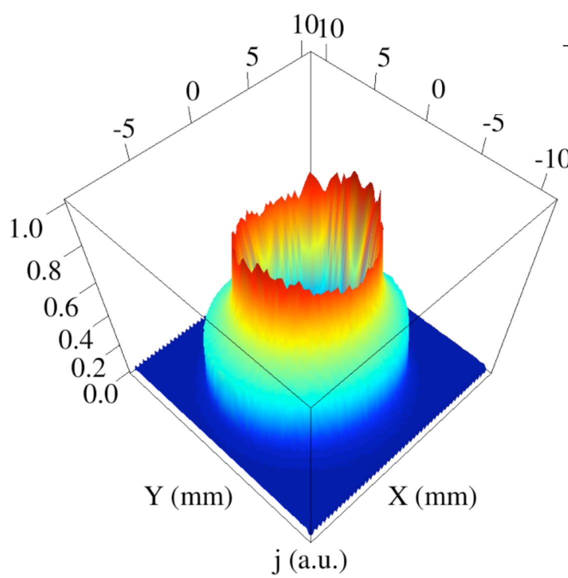
Current density profile of electron beam is shaped by cathode and electrode geometry and maintained by strong solenoidal fields

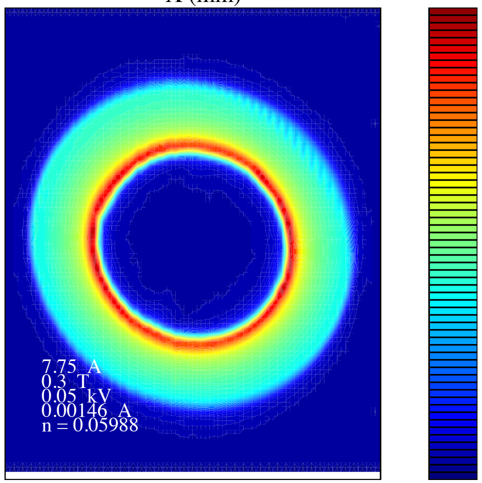
Flat profiles for bunch-by-bunch betatron tune correction



Hollow profile for halo scraping







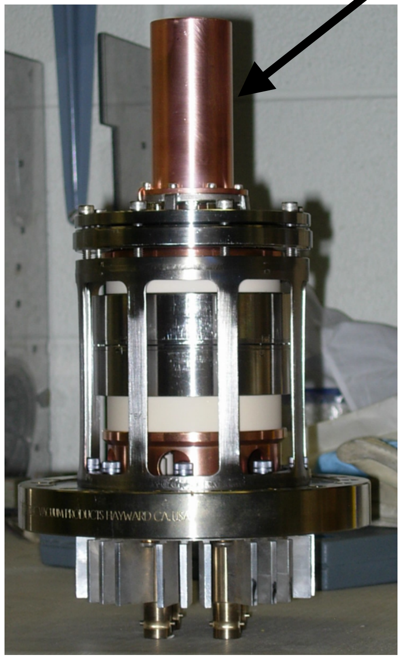
Gaussian profile for compensation of nonlinear beam-beam forces

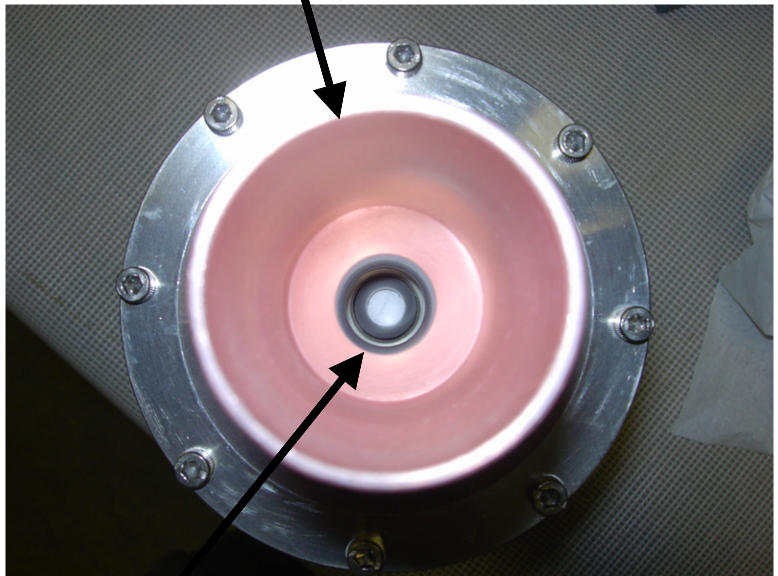
The 15-mm hollow electron gun

side view

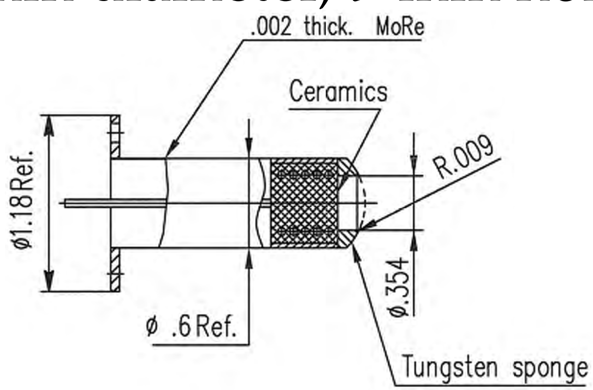
Copper anode

top view



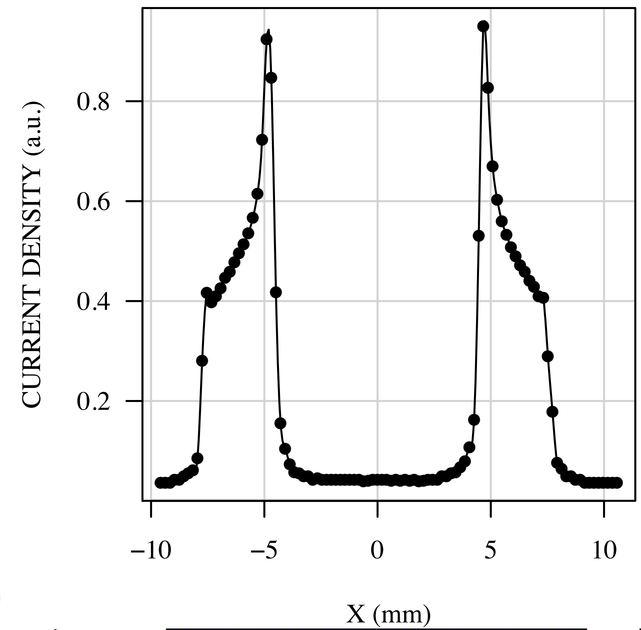


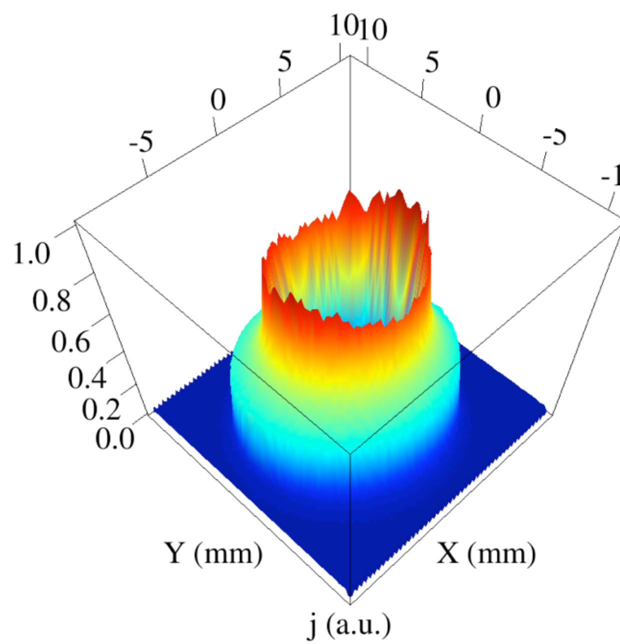
Tungsten dispenser cathode
with convex surface
15-mm diameter, 9-mm hole

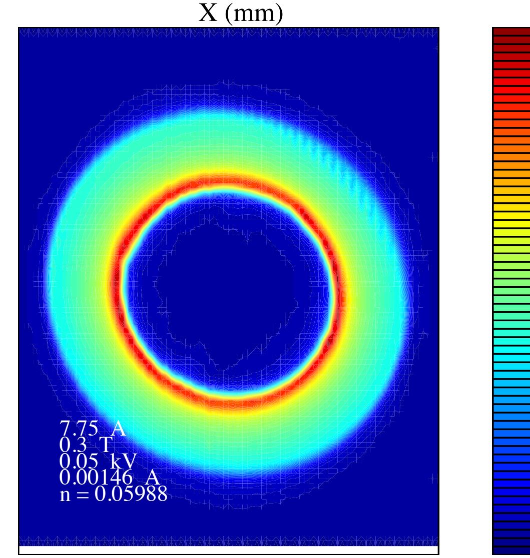


Peak yield: **1.1 A** at 4.8 kV

Profile measurements







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- **Hollow electron beam collimation**
- New accelerator research facilities at Fermilab
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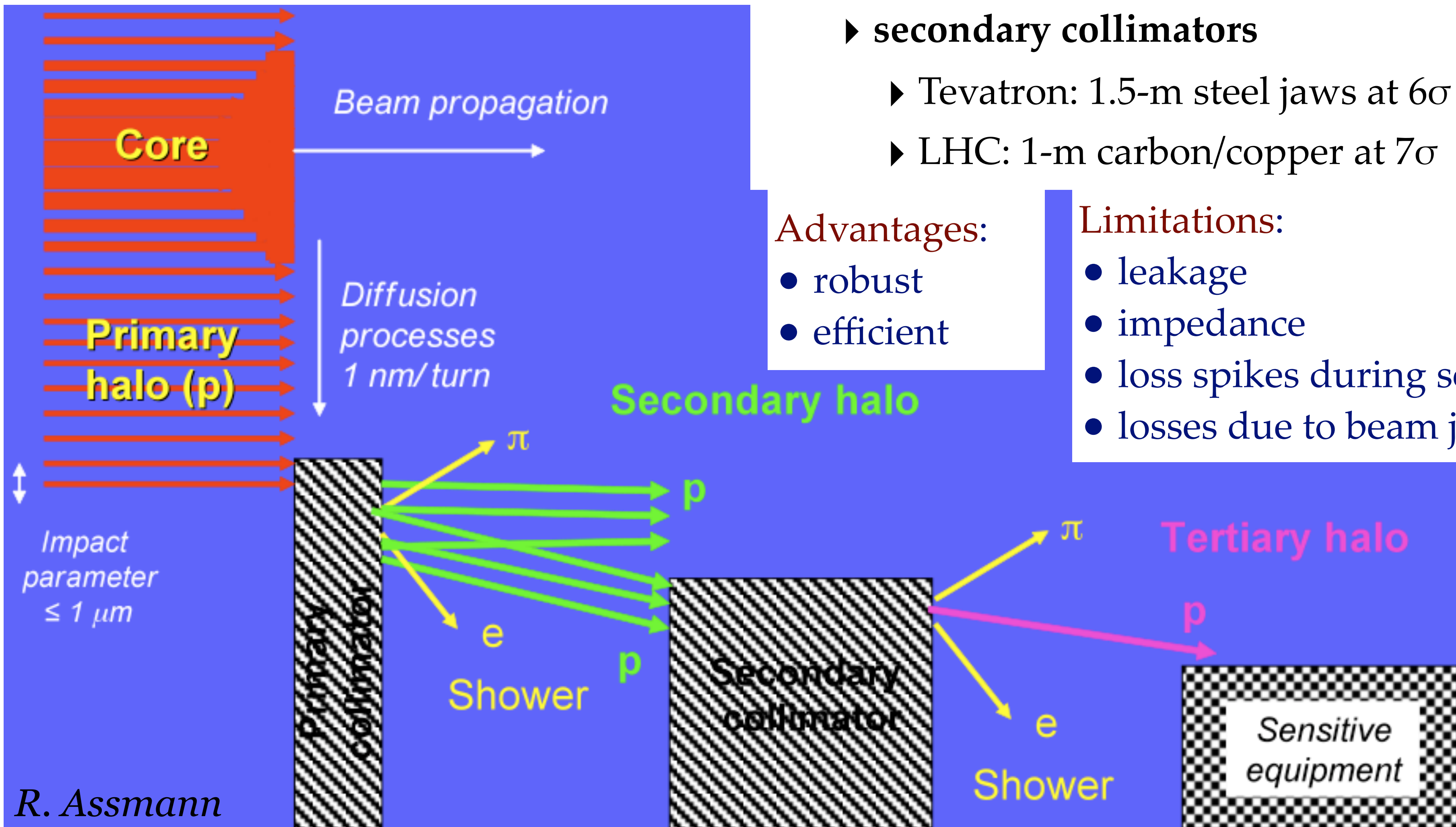
The conventional multi-stage collimation system

- Goals of collimation:
  - reduce beam halo
  - direct losses towards absorbers

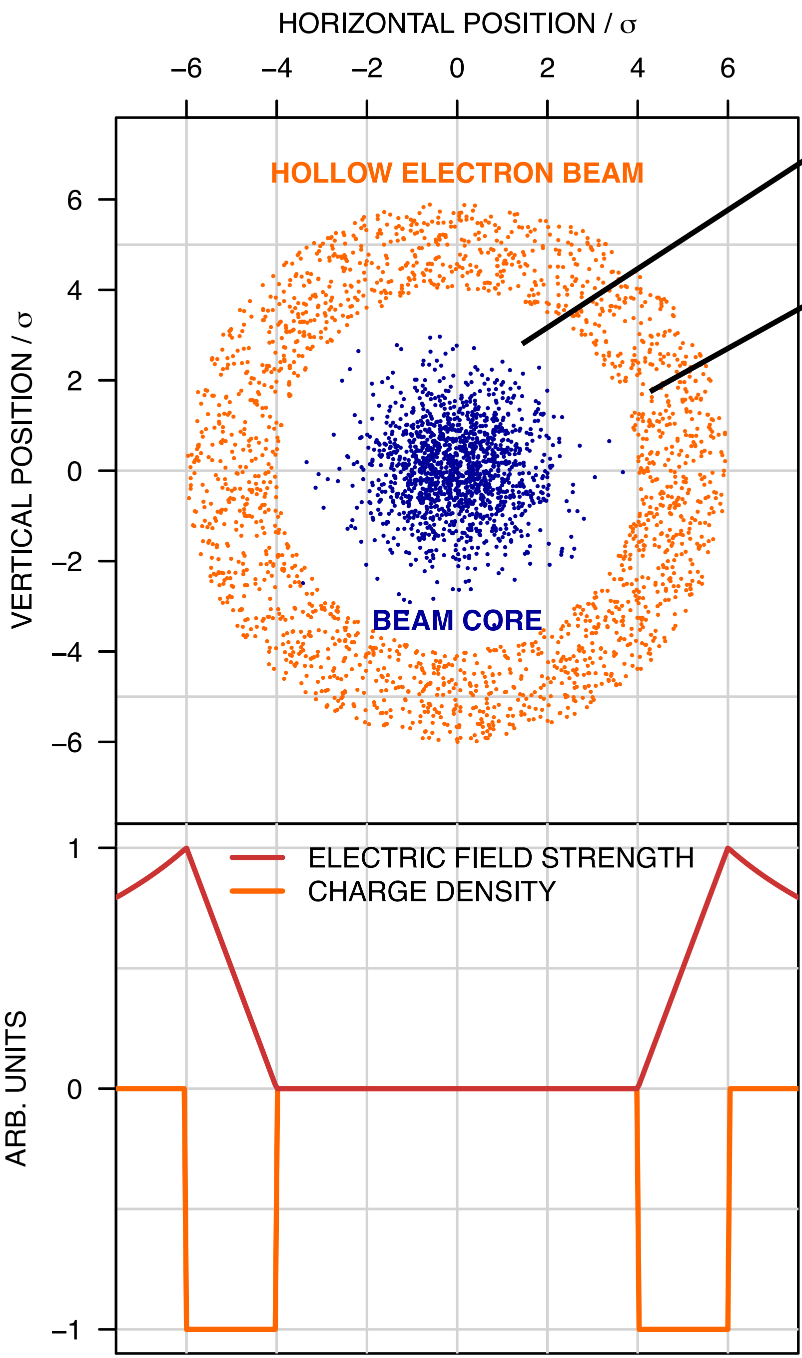
- Conventional schemes:
  - **primary collimators**
    - Tevatron: 5-mm W at 5σ
    - LHC: 0.6-m carbon jaws at 6σ
  - **secondary collimators**
    - Tevatron: 1.5-m steel jaws at 6σ
    - LHC: 1-m carbon/copper at 7σ

Advantages:
- robust
- efficient

Limitations:
- leakage
- impedance
- loss spikes during setup
- losses due to beam jitter



Concept of hollow electron beam collimator



- **Beam core** is unaffected (field-free region)
- **Halo** experiences nonlinear transverse kicks:

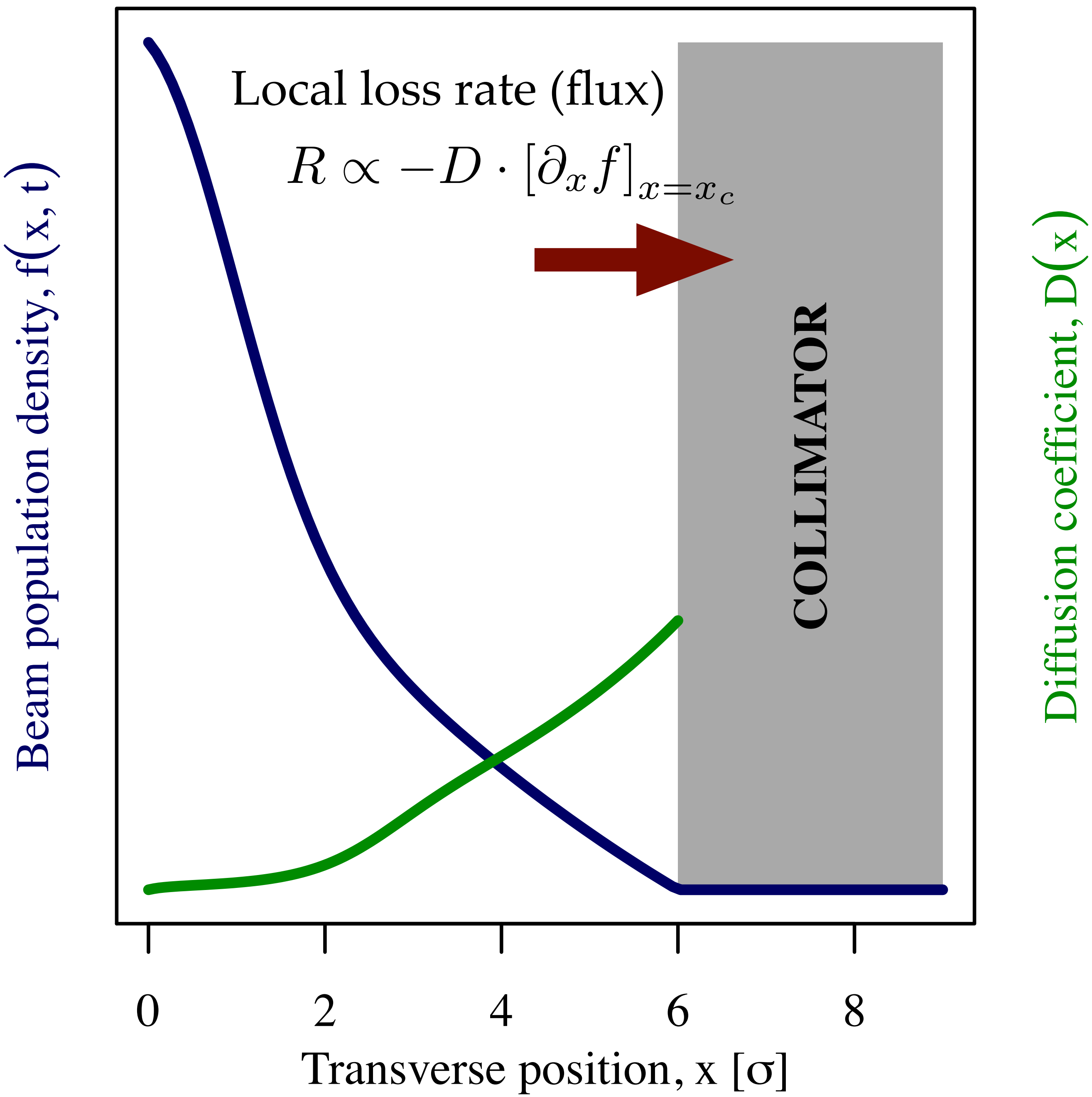
$$\theta_r = \frac{2\, I_r\, L\, (1 \pm \beta_e \beta_p)}{r\, \beta_e\, \beta_p\, c^2\, (B\rho)_p} \left(\frac{1}{4\pi\epsilon_0} \right)$$

About **0.2 µrad** in TEL2 at 0.98 TeV

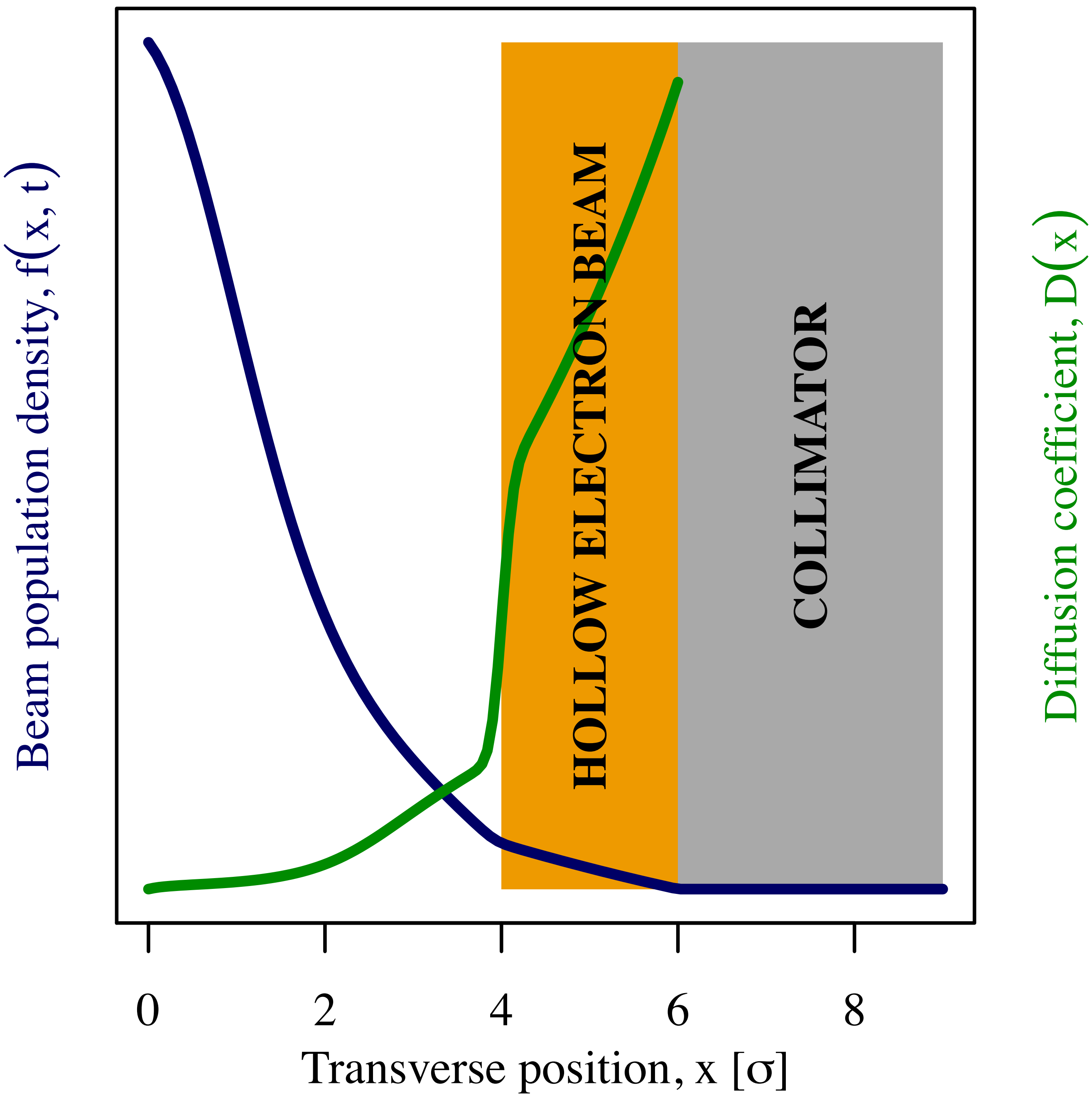
For comparison: multiple Coulomb scattering in Tevatron collimators generates random kicks $\theta_{\mathrm{rms}} = 17\ \mu\mathrm{rad}$

Shiltsev, BEAM06, CERN-2007-002
Shiltsev et al., EPAC08

1-dimensional diffusion cartoon of collimation



1-dimensional diffusion cartoon with hollow electron beam



A good complement to a multi-stage system for high intensities?

ADVANTAGES

- Can be close to or even overlap with the main beam
- No material damage
- Continuously variable strength (“variable thickness”)
- Works as “soft scraper” by enhancing diffusion
- Resonant excitation is possible for faster removal (pulsed operation)
- Low impedance
- No ion breakup
- Position control by magnetic fields (no motors or bellows)
- Established electron-cooling / electron-lens technology

POTENTIAL ISSUES

- Critical
  - beam alignment
  - symmetry of electron beam profile
- Stability of beams at high intensity
- Cost

Experimental studies of hollow electron beam collimation

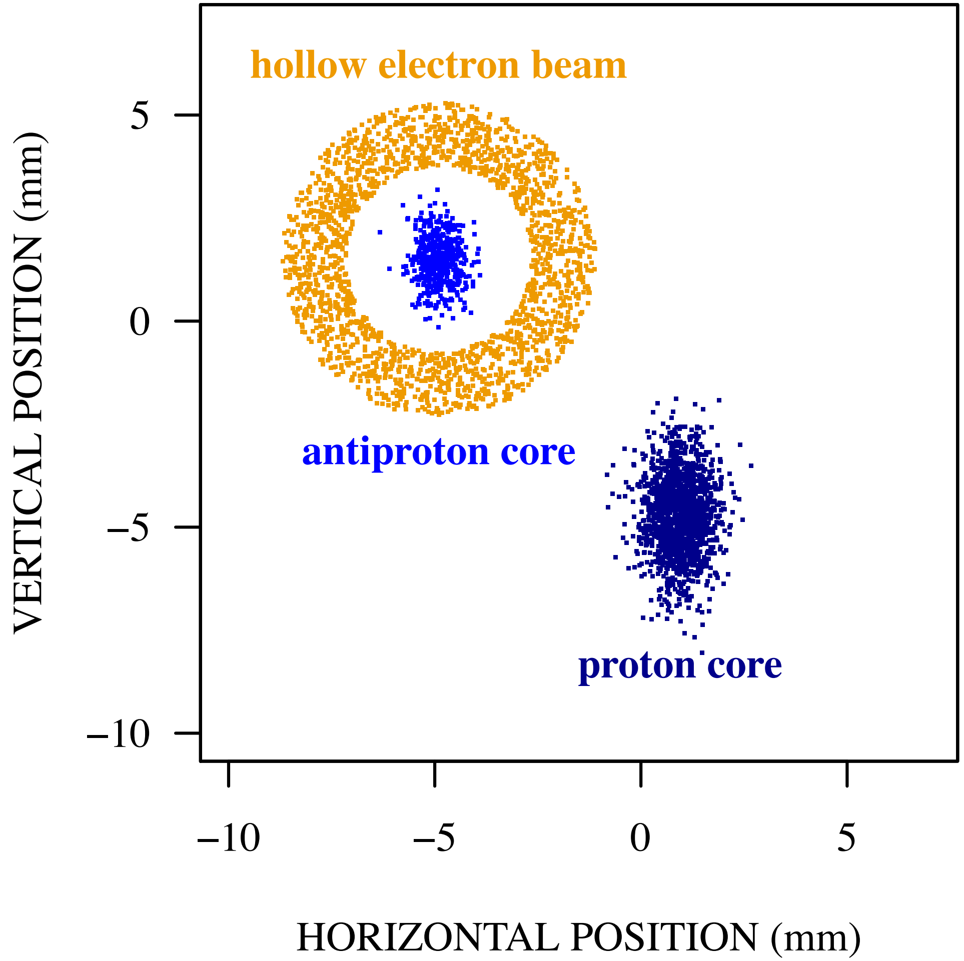
- Tevatron experiments (Oct. ‘10 - Sep. ’11) provided experimental foundation
- Main results
  - **compatibility with collider operations**
  - **alignment** is reliable and reproducible
  - **smooth halo removal**
  - **removal rate vs. particle amplitude**
  - **negligible effects on the core** (particle removal or emittance growth)
  - **suppression of loss-rate fluctuations** (beam jitter, tune changes)
  - effects on **collimation efficiency**
  - transverse beam halo **diffusion enhancement**

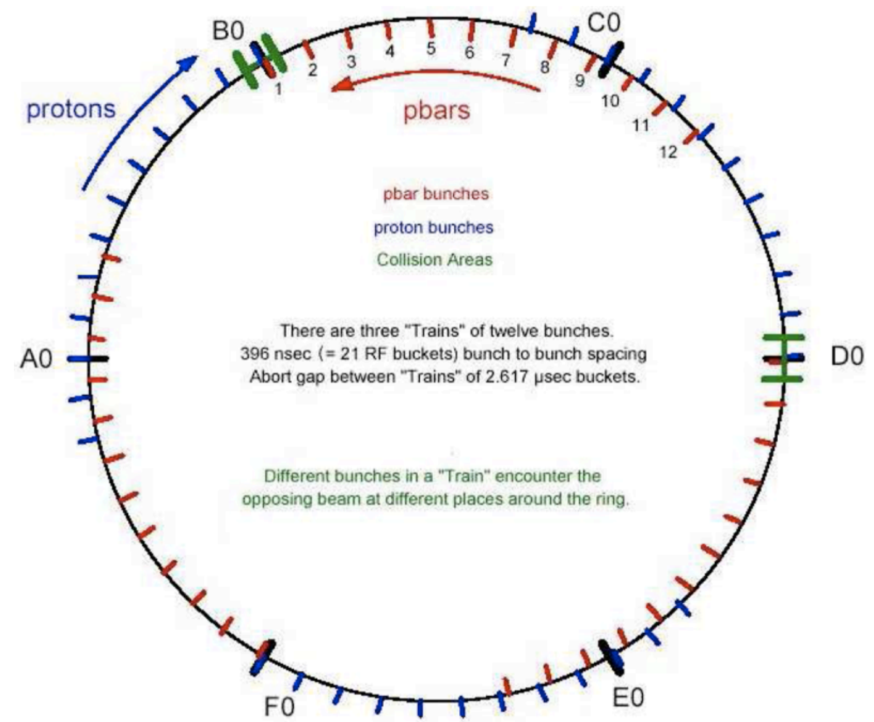
Stancari et al., Phys. Rev. Lett. **107**, 084802 (2011)
Stancari et al., IPAC11 (2011)
Stancari, APS/DPF Proceedings, arXiv:1110.0144 [physics.acc-ph]

Layout of the beams in the Tevatron

Proton and antiproton beams in the same vacuum pipe

Transverse separation was 9 mm in electron lens

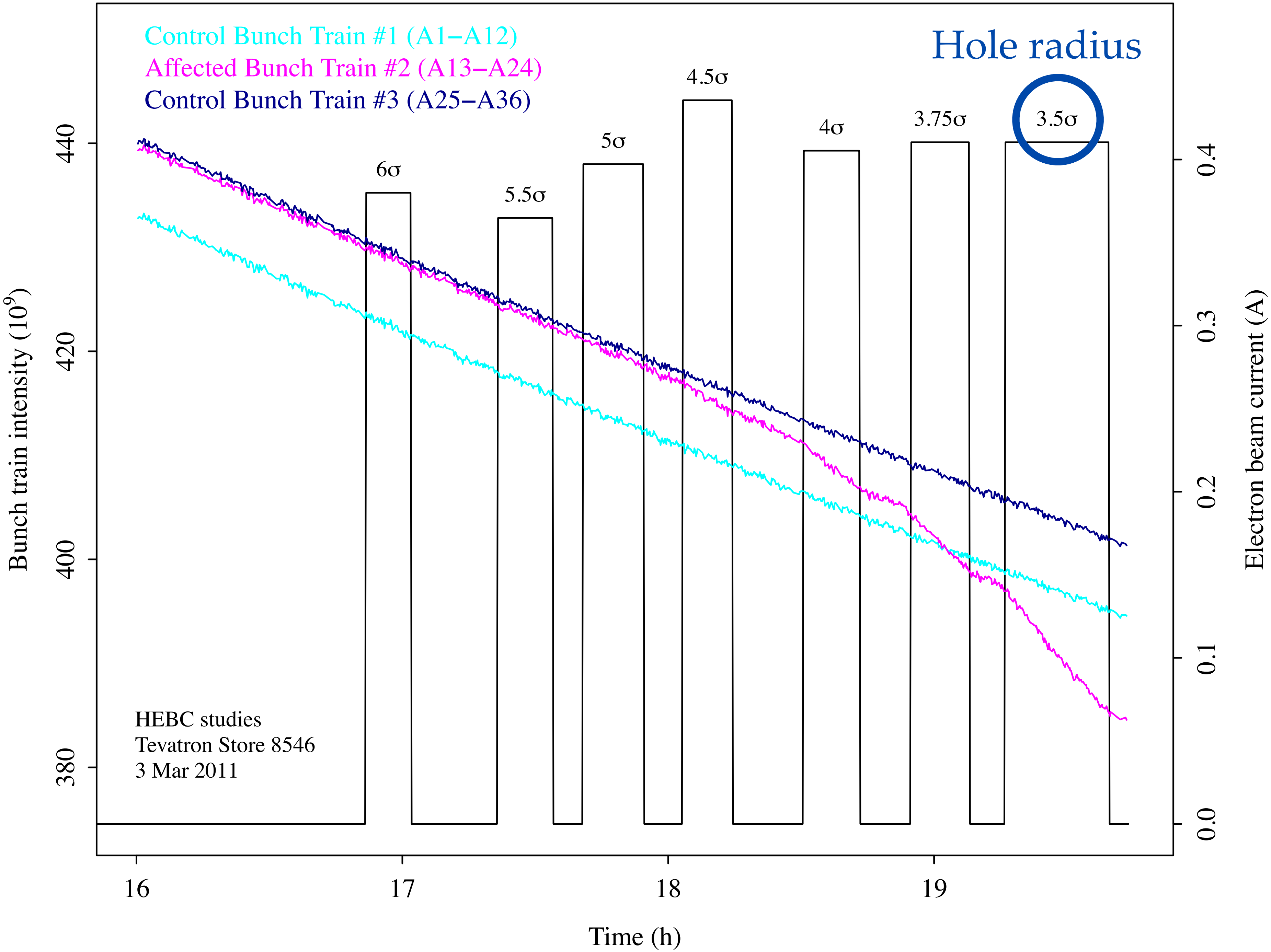




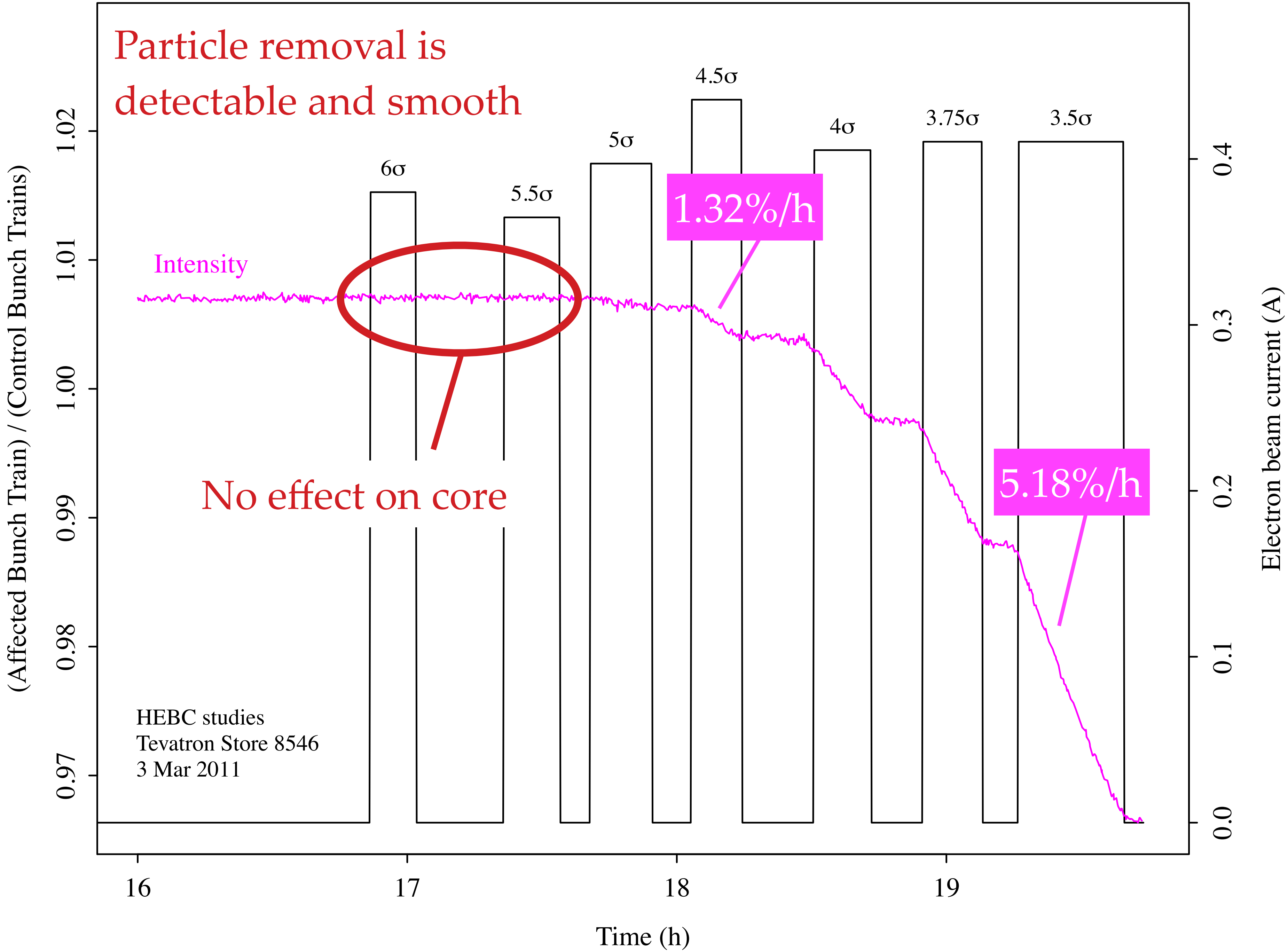
3 trains of 12 bunches each

396 ns bunch separation

Scraping of 1 antiproton bunch train



Removal rate: affected bunch train relative to other 2 trains



Is the core affected? Are particles removed from the halo?

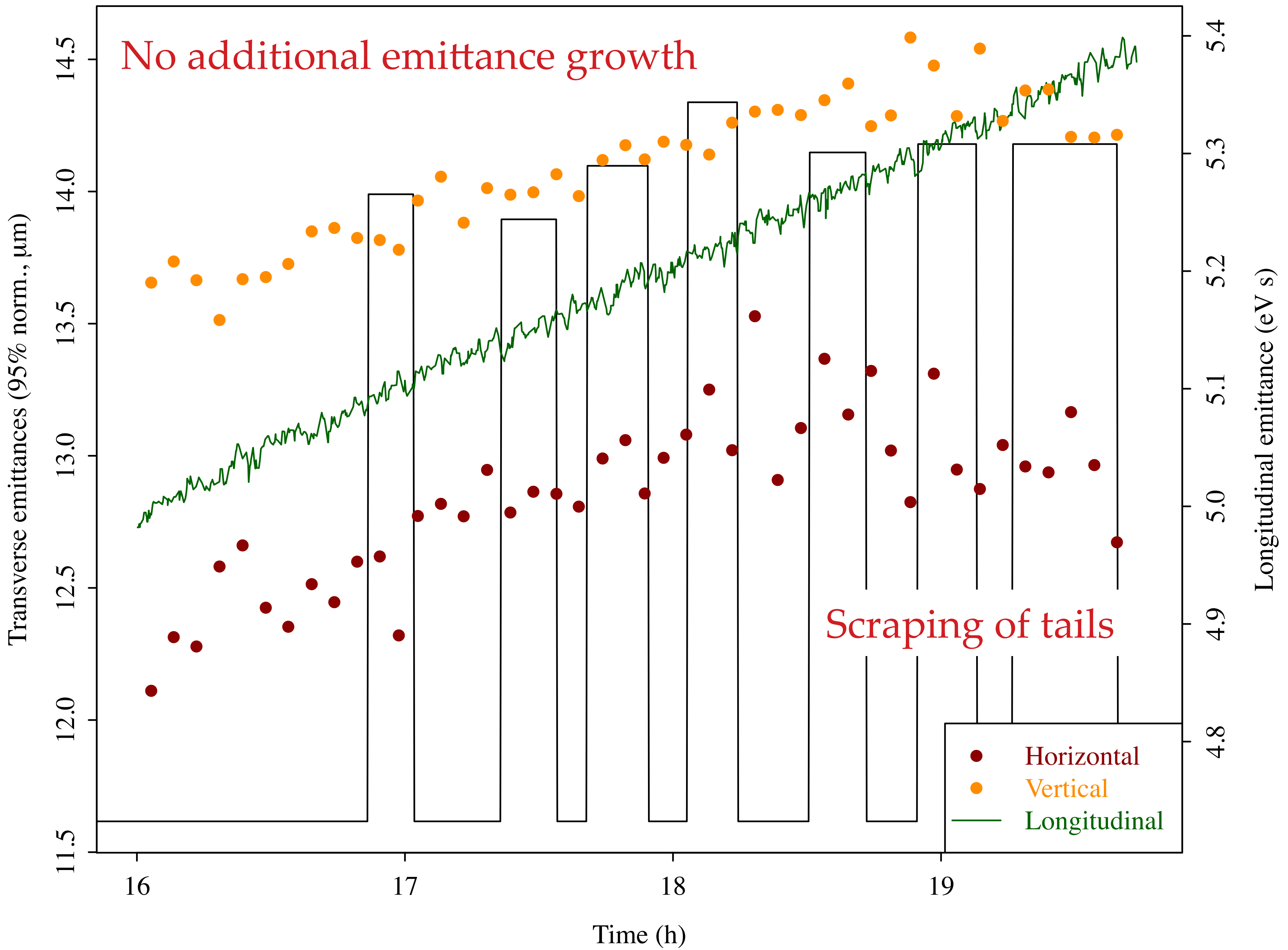
Several strategies:

- **No removal** with large electron beam inner radius (previous slide)
- Check **emittance** evolution
- Compare **intensity** and **luminosity** change when scraping antiprotons:

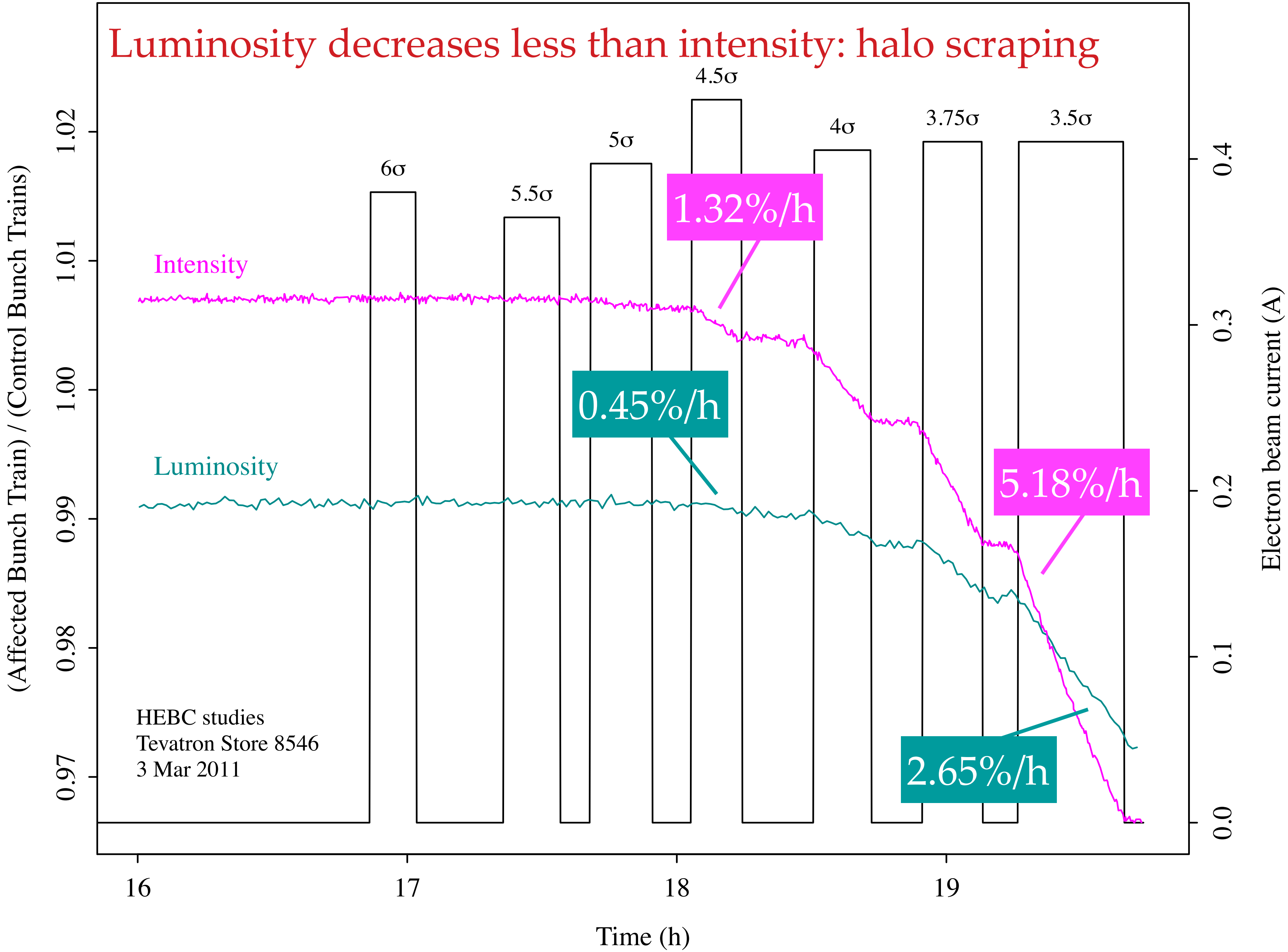
$$\mathcal{L} = \left(\frac{f_{\mathrm{rev}} N_b}{4\pi} \right) \frac{N_p N_a}{\sigma^2} \qquad \frac{\Delta \mathcal{L}}{\mathcal{L}} = \frac{\Delta N_p}{N_p} + \frac{\Delta N_a}{N_a} - 2 \frac{\Delta \sigma}{\sigma}$$

  - same fractional variation if other factors are constant
  - luminosity decreases more if there is emittance growth or proton loss
  - luminosity decreases less if removing halo particles (smaller relative contribution to luminosity)
- **Removal rate** vs. amplitude (collimator scan, steady state)
- **Diffusion rate** vs. amplitude (collimator scan, time evolution of losses)

Emittances of affected bunch train



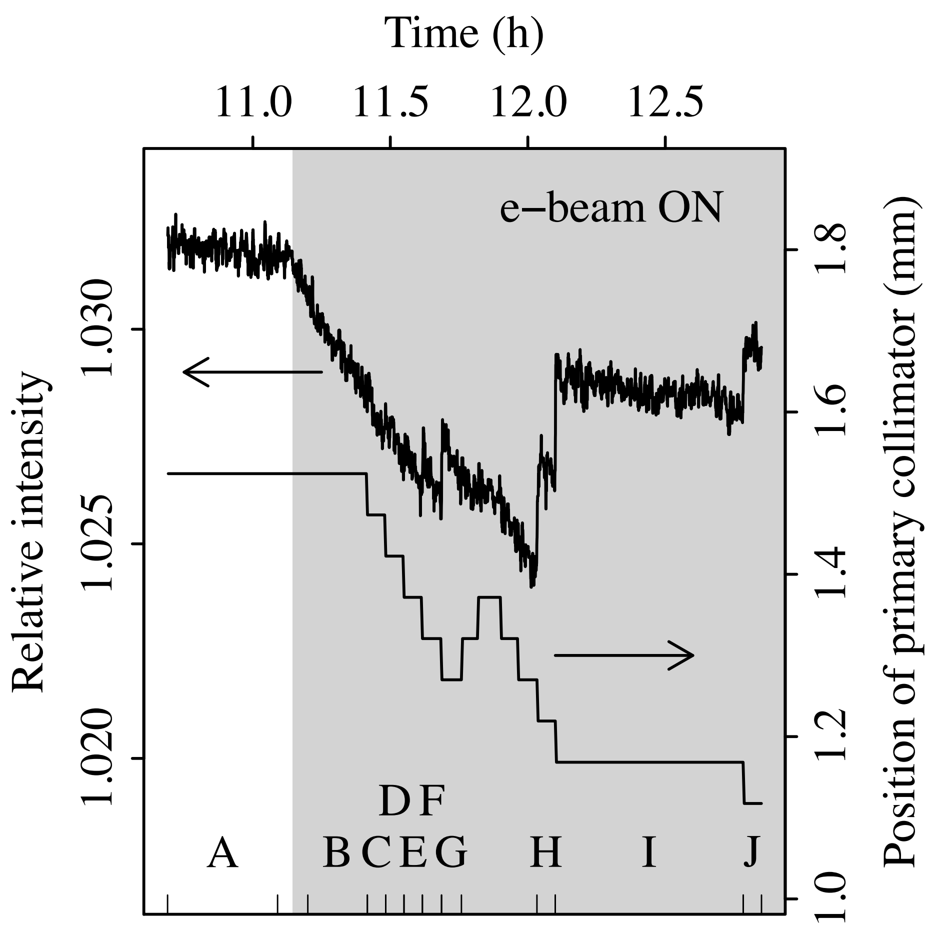
Relative intensity and luminosity of affected bunch train

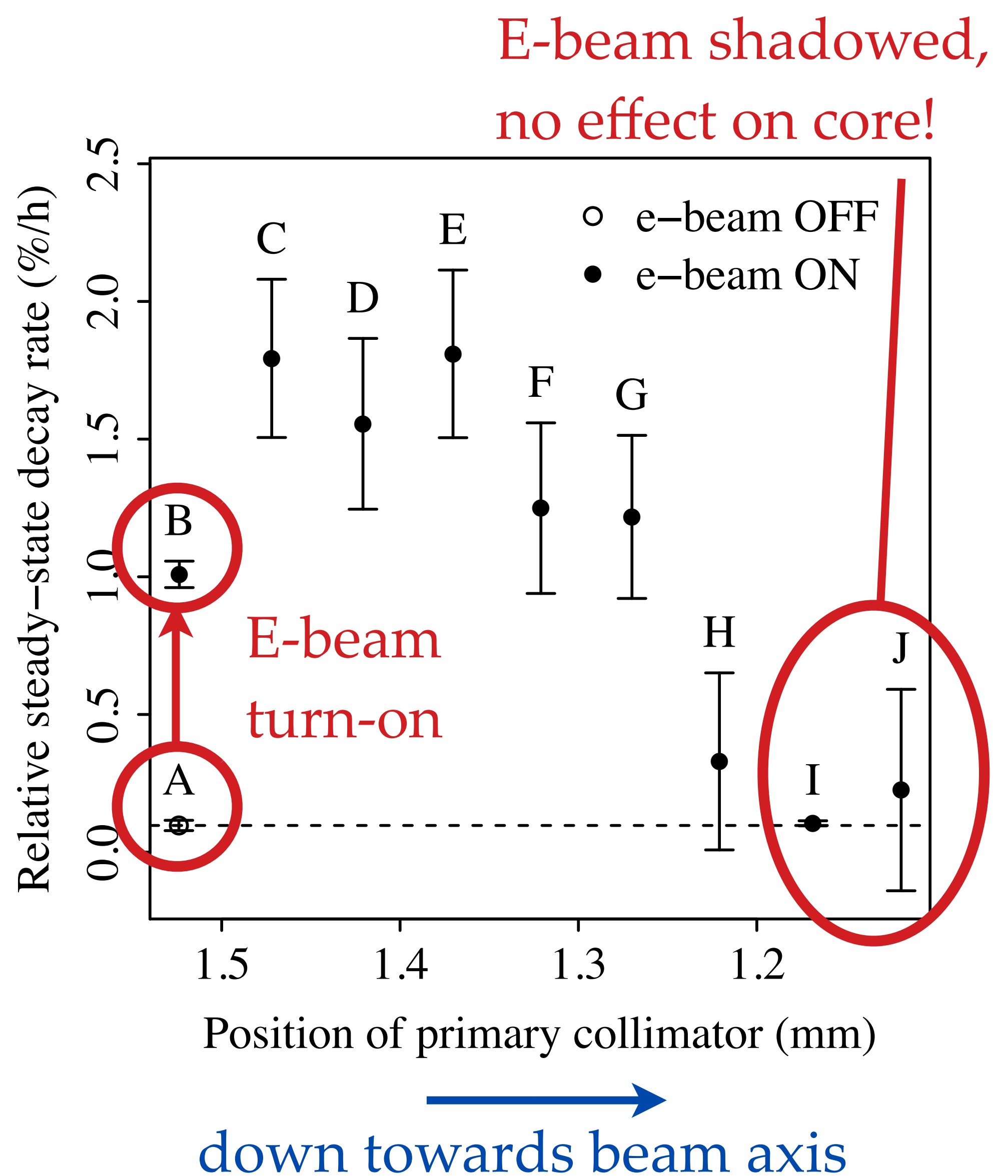


Removal rate vs. amplitude from collimator scan

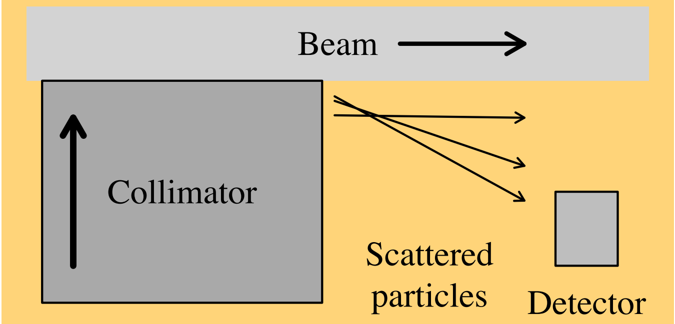
Electrons (0.15 A) on pbar train #2, 3.5σ hole (1.3 mm at collimator)

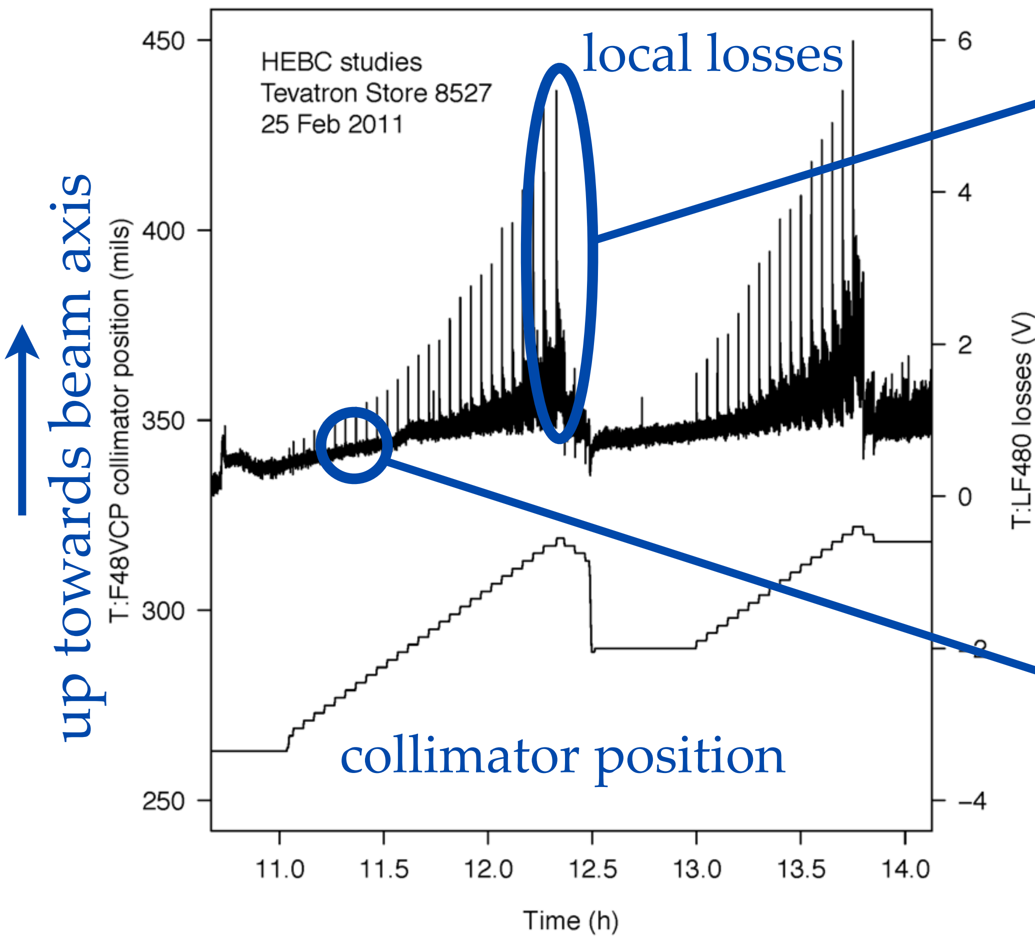
Vertical scan of primary collimator (others retracted)



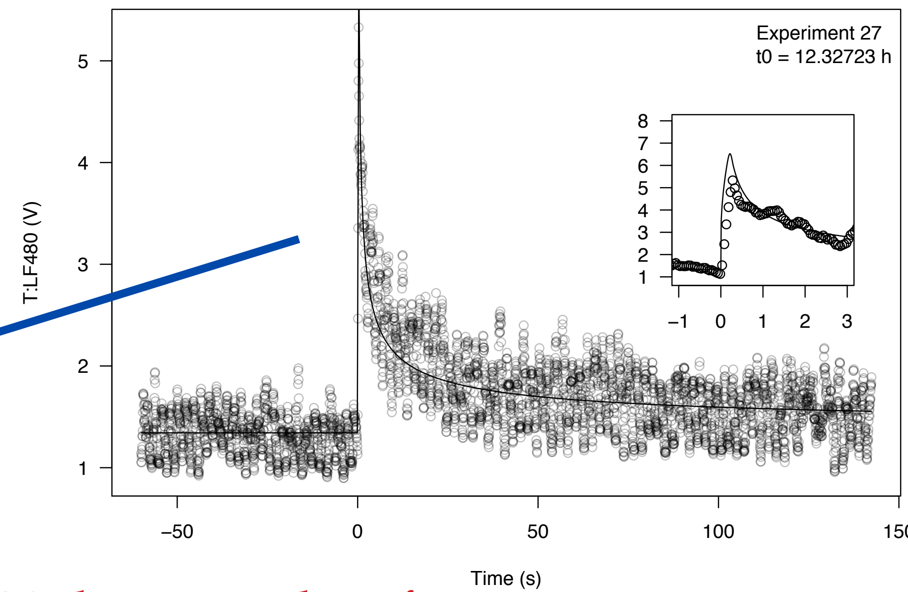


Measurement of diffusion rate vs. amplitude with collimator scans

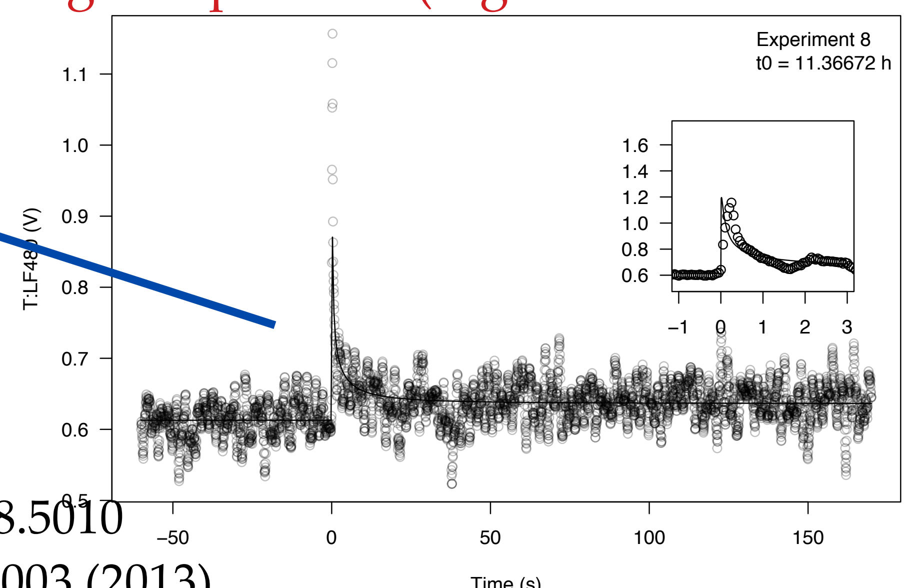




Mess and Seidel, NIMA **351**, 279 (1994)



Tails repopulate faster at large amplitudes (higher diffusion rate)



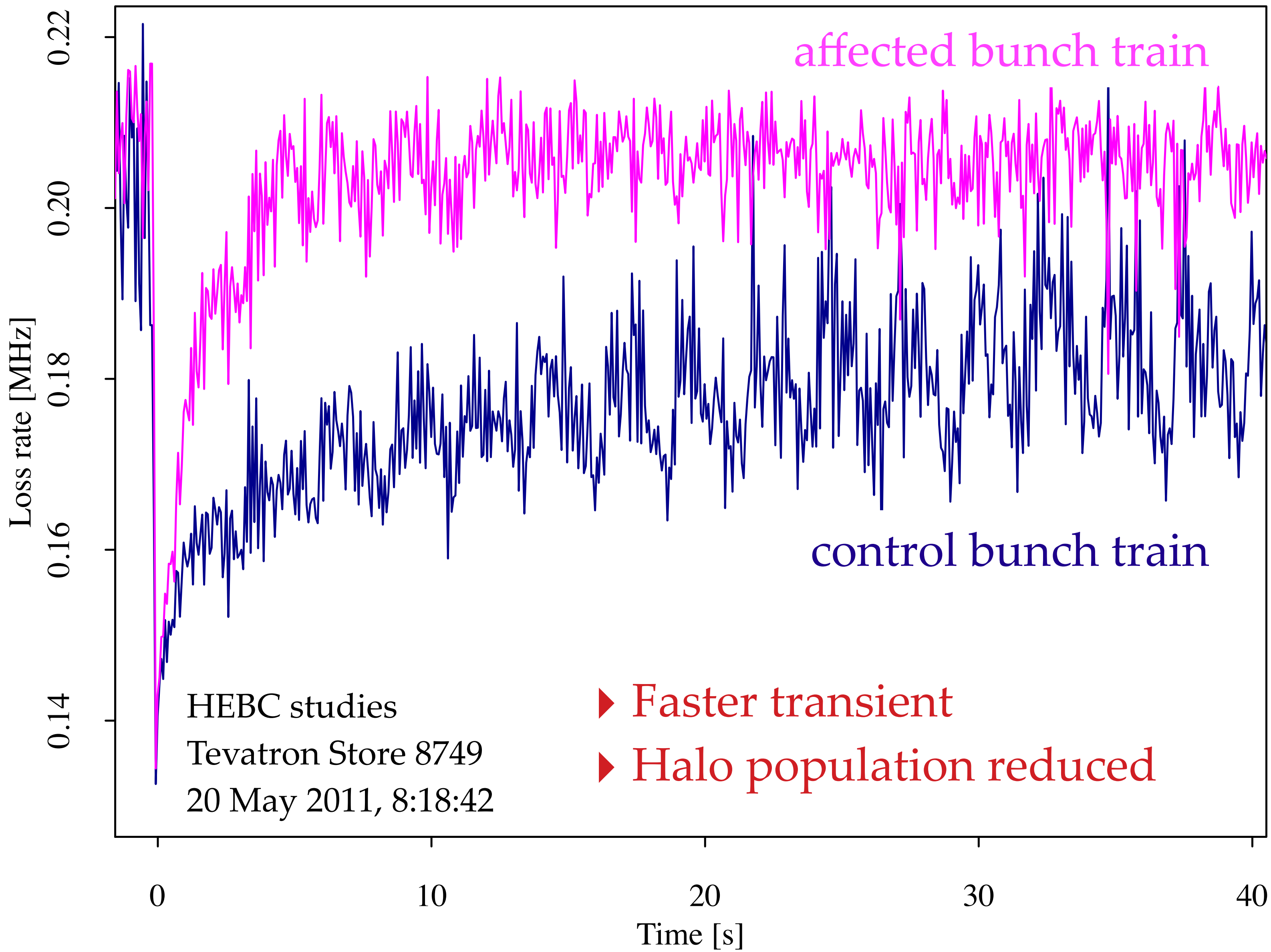
Stancari et al., IPAC11, HB2012, BB2013, arXiv:1108.5010

Valentino et al., Phys. Rev. ST Accel. Beams **16**, 021003 (2013)

Measured effect of the hollow electron lens on diffusion in the Tevatron

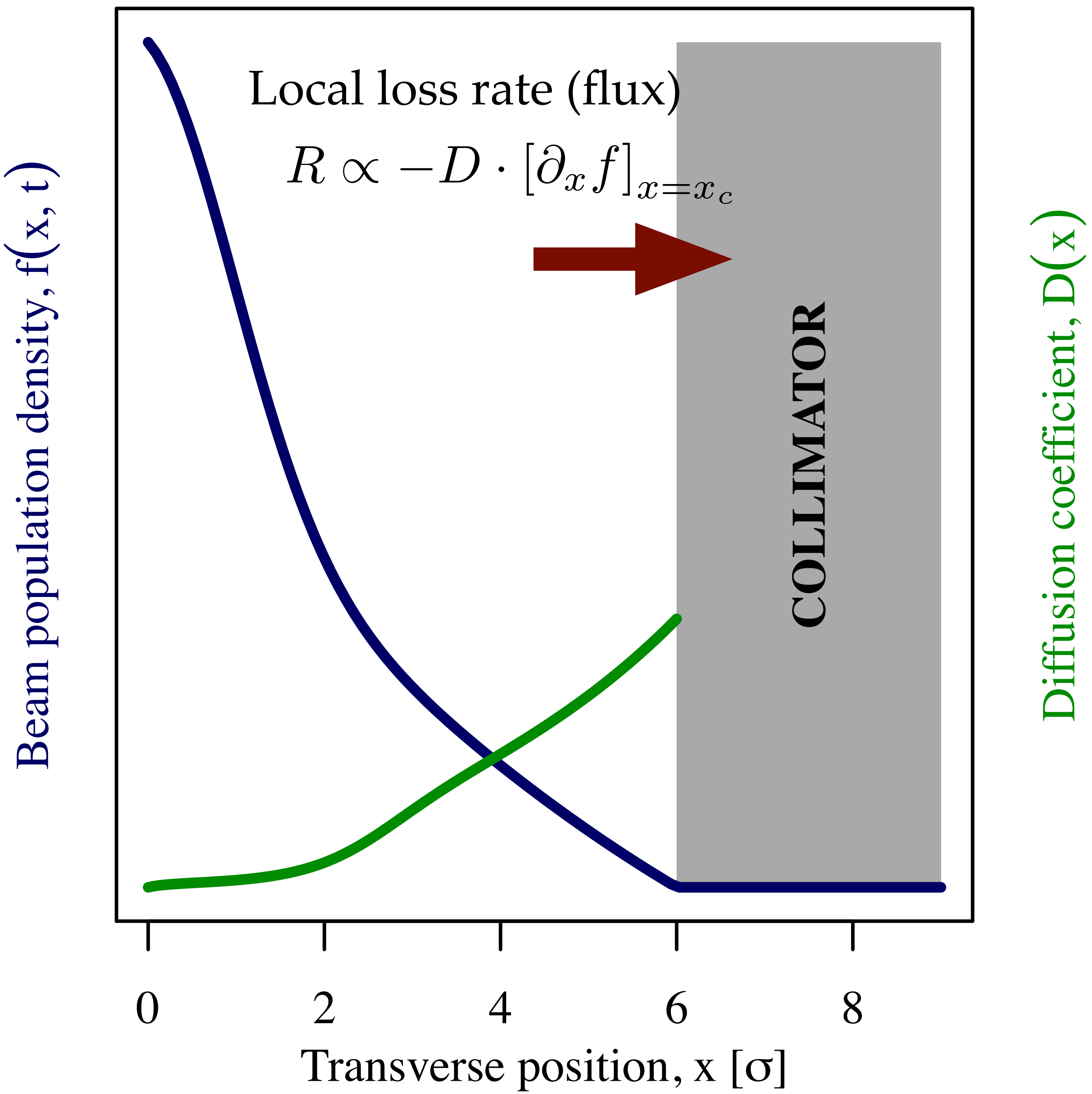
Electrons (0.9 A) on pbar train #2, 4.25σ hole

Example of **vertical collimator step out**, 50 μm



- Faster transient
- Halo population reduced

1-dimensional diffusion cartoon of collimation



Diffusion model of loss rate evolution in collimator scans

Stancari, arXiv:1108.5010 [physics.acc-ph]

Distribution function evolves under diffusion with boundary condition at collimator

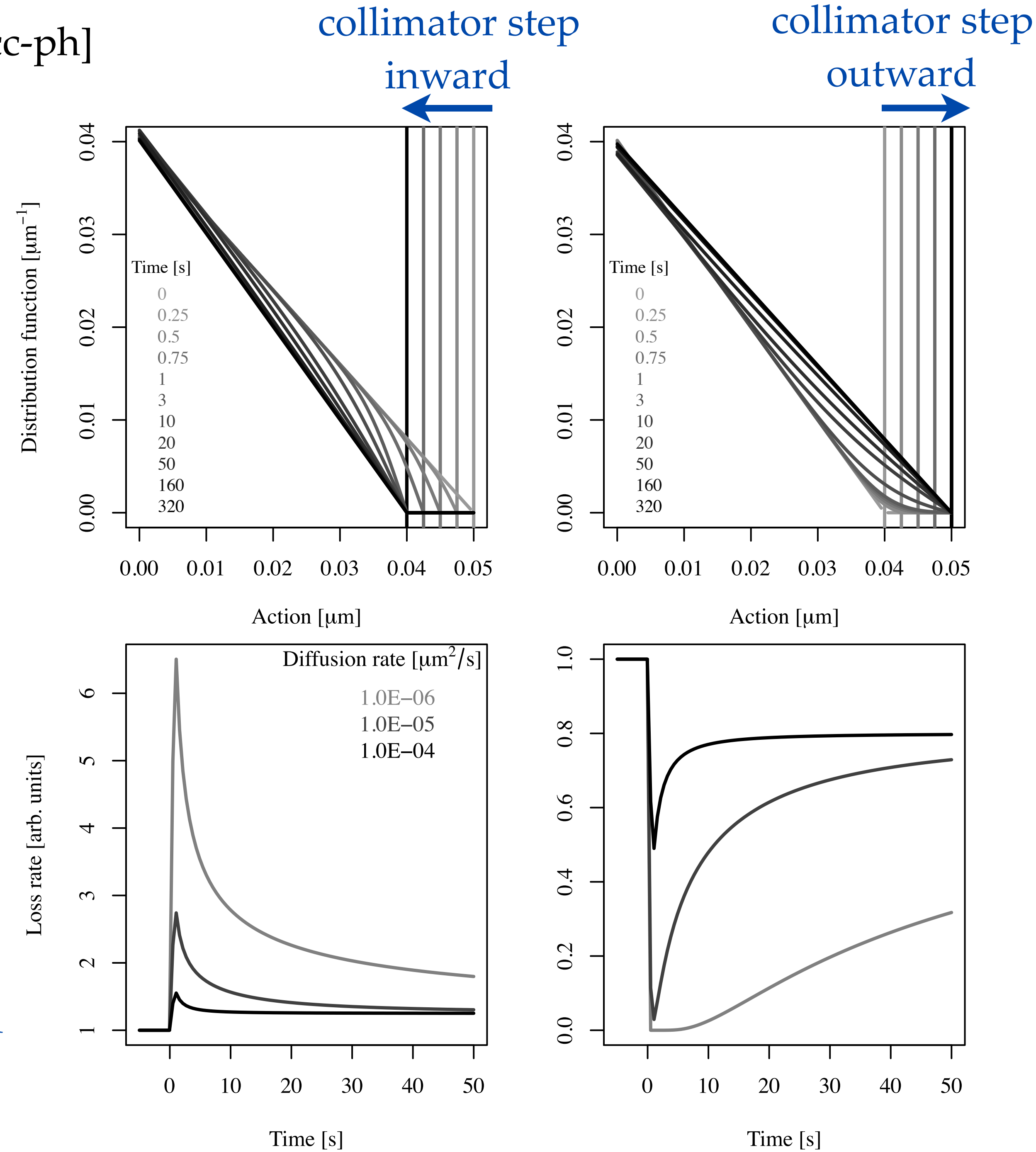
$$\partial_t f = \partial_J \left(D \cdot \partial_J f \right)$$

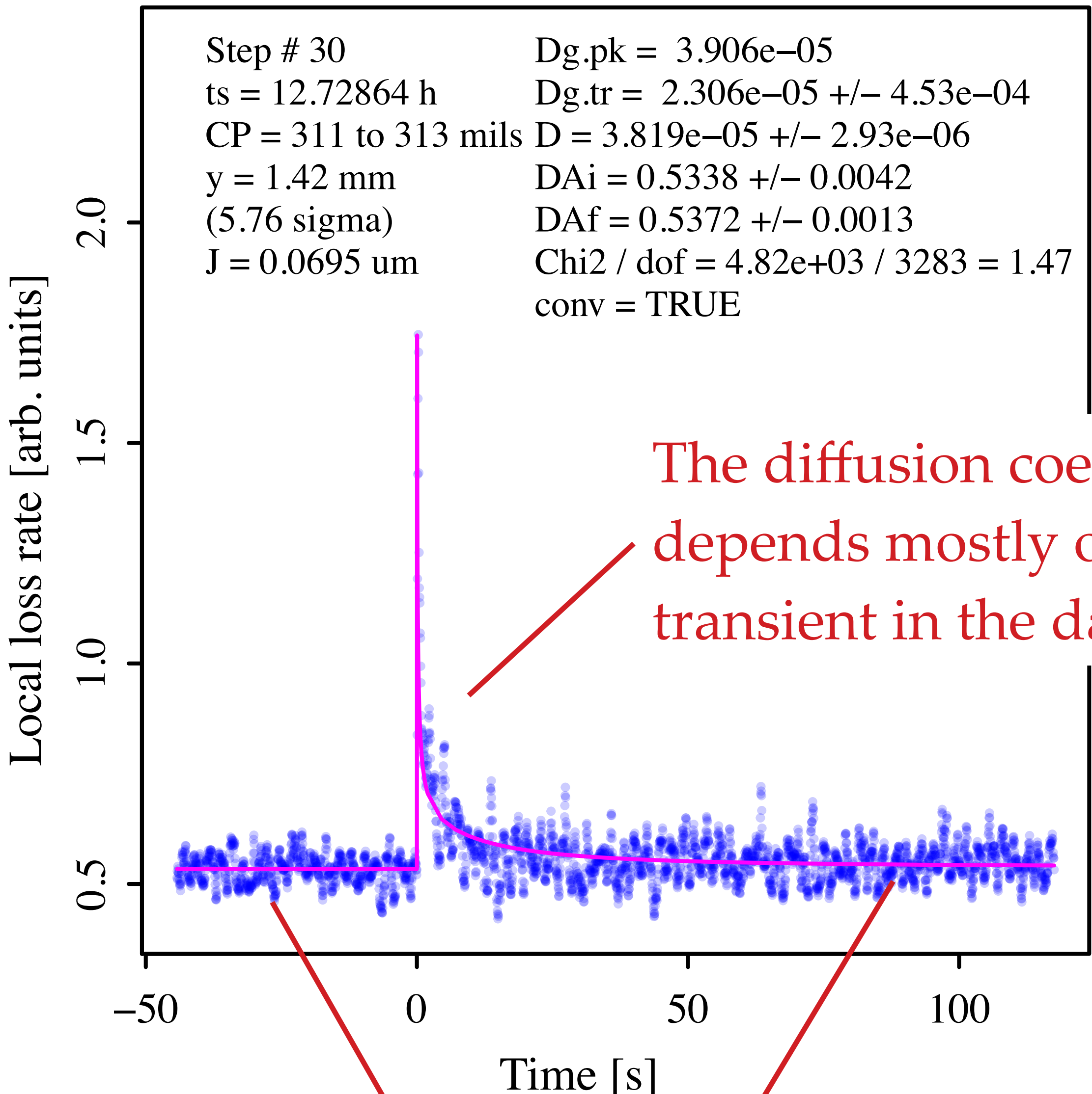
Instantaneous loss rate is proportional to slope of distribution function

$$R = -k \cdot D \cdot \left[\partial_J f \right]_{J=J_c} + B$$

loss monitor calibration

background rate

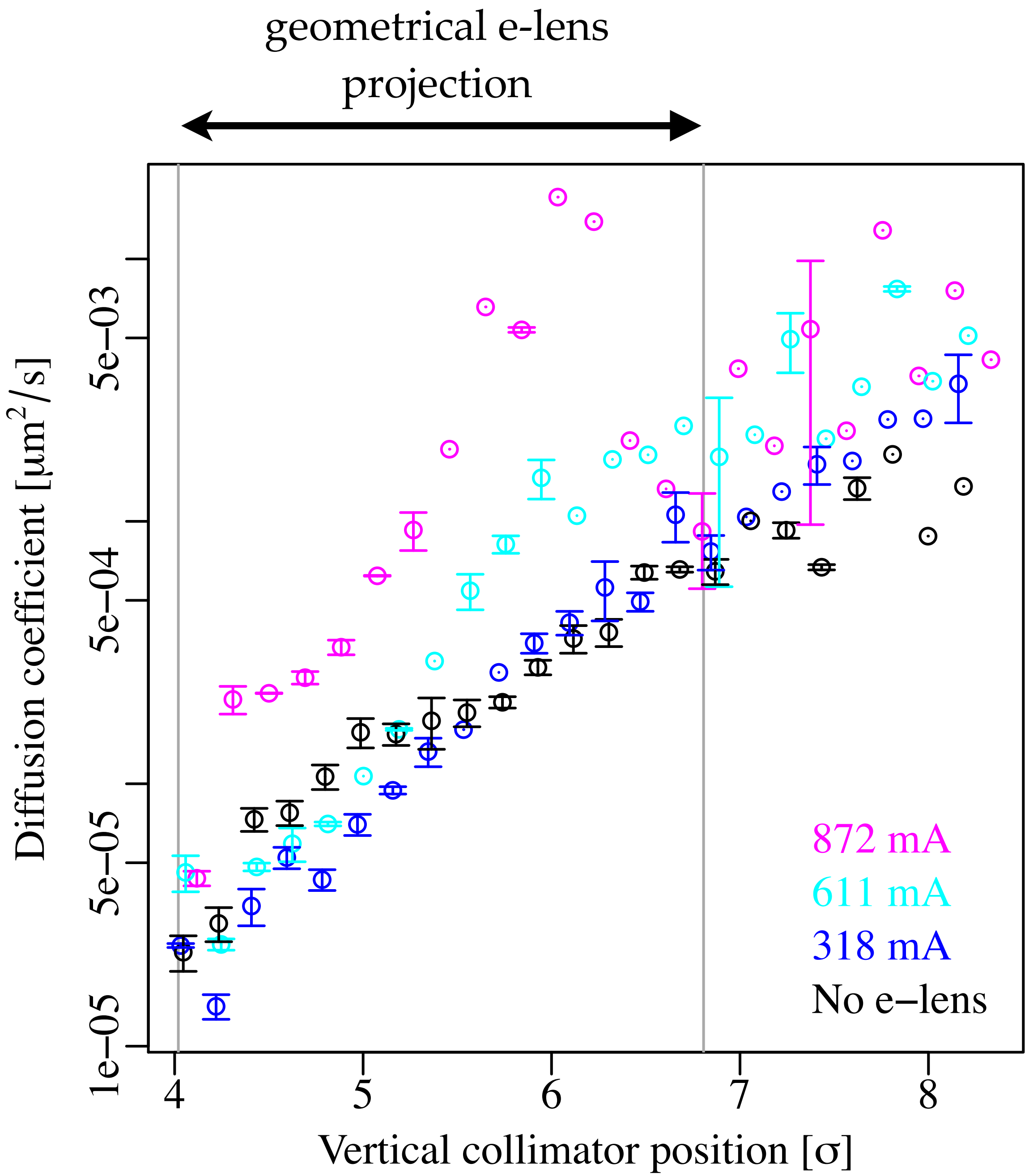




The diffusion coefficient depends mostly on the transient in the data

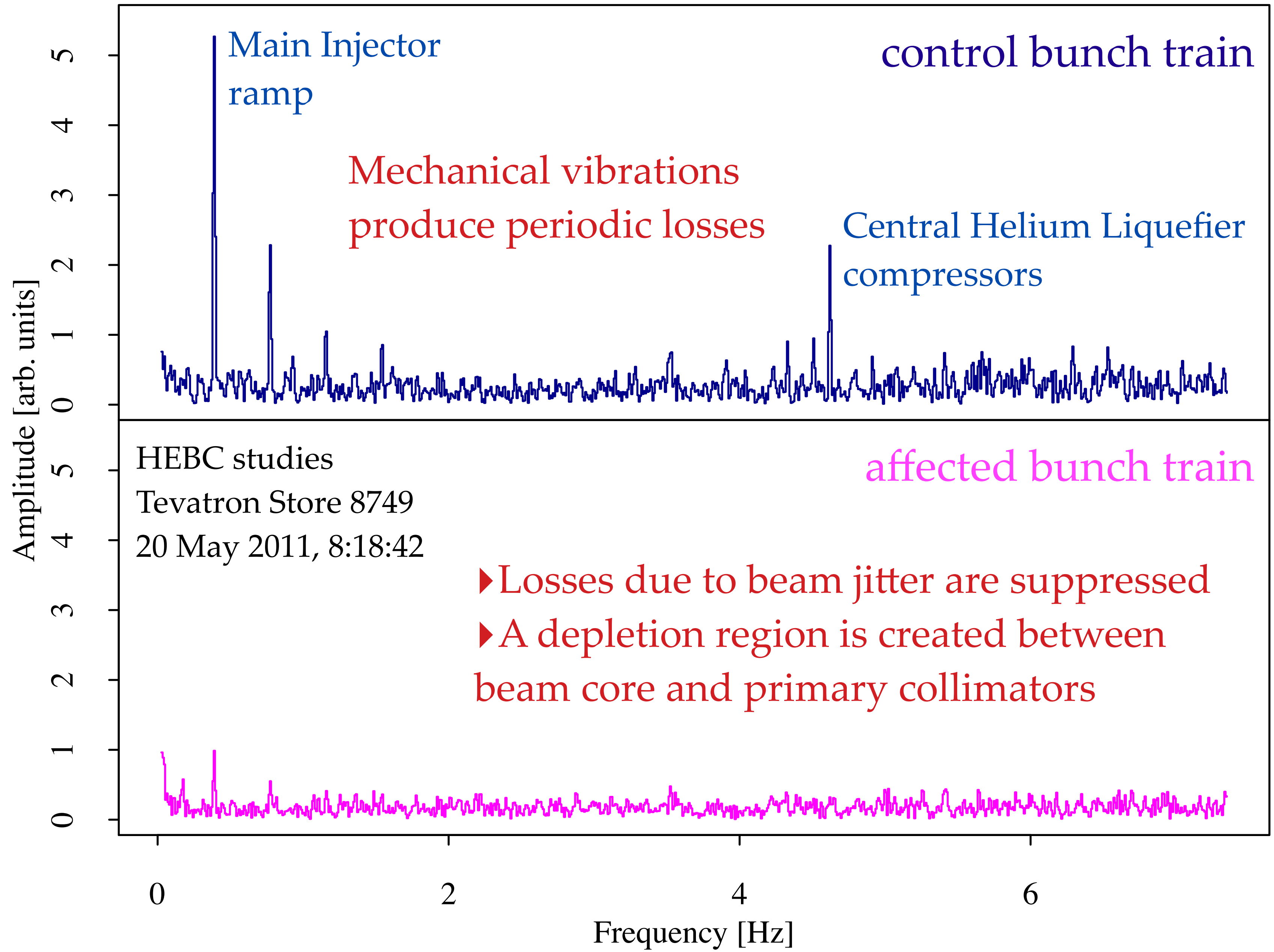
Particle fluxes before and after the step are determined by the steady-state loss levels

Measured effect of the hollow electron lens on diffusion in the Tevatron

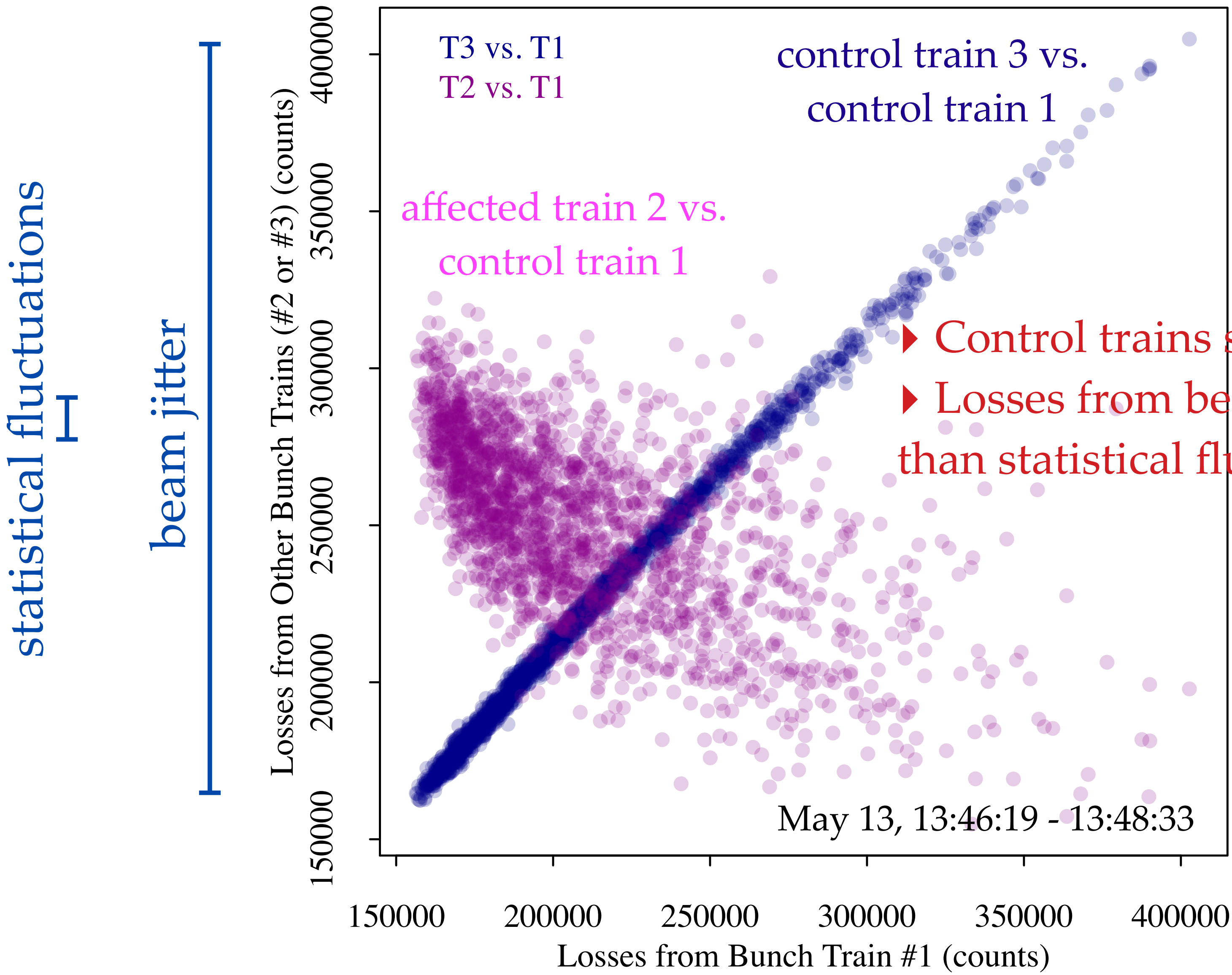


Large diffusion
enhancement
in halo region

Effect of hollow electron beam on periodic losses



Effect of hollow electron beam on loss correlations



- Control trains strongly correlated
- Losses from beam jitter much larger than statistical fluctuations

- Hollow beam eliminates correlations among trains
- Interpretation: larger diffusion rate, lower tail population, less sensitive to jitter

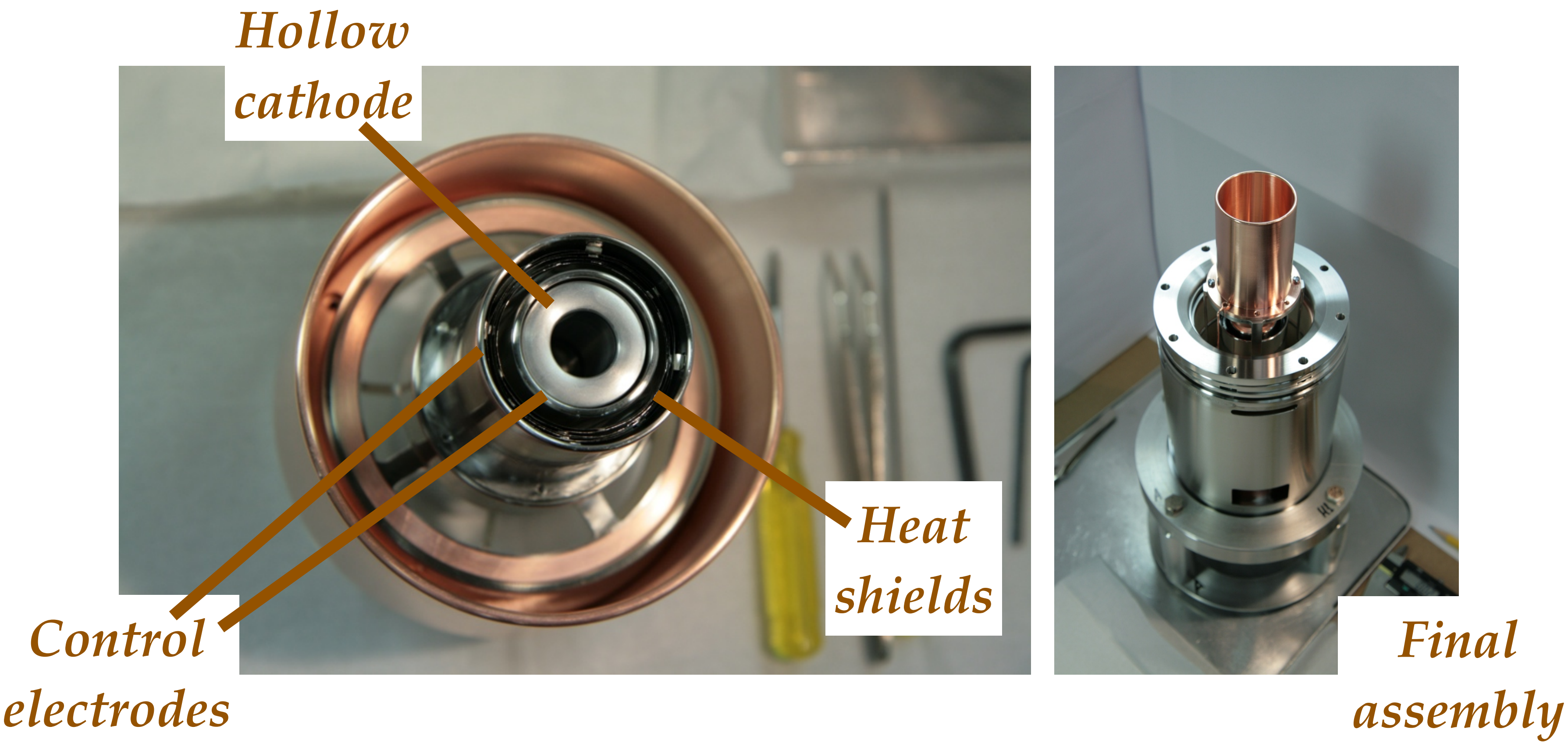
A good complement to the LHC collimation system?

- **Scraping in the LHC**. Stored beam energy: **350 MJ**! (2 MJ in Tevatron)
  - No dedicated scraping devices; primaries currently best option
  - Scraping with primaries limited in speed and range; almost excluded at top energy and full intensity
  - Scraping at injection is not effective because of continuous tail repopulation
- **Possible uses of hollow electron lenses** suggested by 2012 operations
  - Control losses during all phases: ramp, squeeze, adjust
  - Reduce sensitivity to orbit drifts during squeeze
  - Remove tails before they are lost in collisions
  - Limit halo during physics run
  - Machine protection for single-turn crab-cavity failures
- Other uses of electron lenses (with different current profiles)?
  - tune-spread control to mitigate instabilities, ...

Strategy and plans

- Final collimation needs and decisions can only be defined after gaining operational experience at 7 TeV (2015)
  - cleaning efficiency, lifetimes, quench limits, impedances
- Proceed with design of 2 devices within the U.S. LHC Accelerator Research Program (LARP) and European HiLumi LHC Design Study:
  - conceptual design Nov. 2013
  - technical design in 2014
  - construction 2015-2017
  - installation during 2018 long shutdown (2022 if limited by resources)
- Investigate proposed alternative schemes
  - damper excitation, tune modulation, beam-beam wire compensators
- Build electron lens competence at CERN
- Develop nondestructive, direct halo diagnostics
- If possible, extend Tevatron experience with beam tests at RHIC?

25-mm hollow electron gun, LHC prototype



- 25 mm outer diameter, 13.5 inner diameter
- Built and characterized at Fermilab electron-lens test stand
- Yields up to 5 A at 10 kV

Main goals of numerical simulations

- **Would hollow electron beam collimation be effective in the LHC?**
  - The kicks are nonlinear, with a small random component. Halo removal rates are expected to depend on magnetic rigidity of the beam, machine lattice, and noise sources. Nontrivial extrapolation from Tevatron to LHC.
- **Would there be any adverse effects on the core, such as lifetime degradation or emittance growth?**
  - No effects were seen in the Tevatron in continuous mode. Effects of asymmetries in resonant operation?
- **Methods**
  - Lifetrac and SixTrack codes
  - Machine models with nonlinearities
  - Uniform halo population, replenishing mechanisms to be implemented
    - Diffusion was measured in both Tevatron and LHC
  - Ideal electron lens, profile imperfections, injection/extraction bends

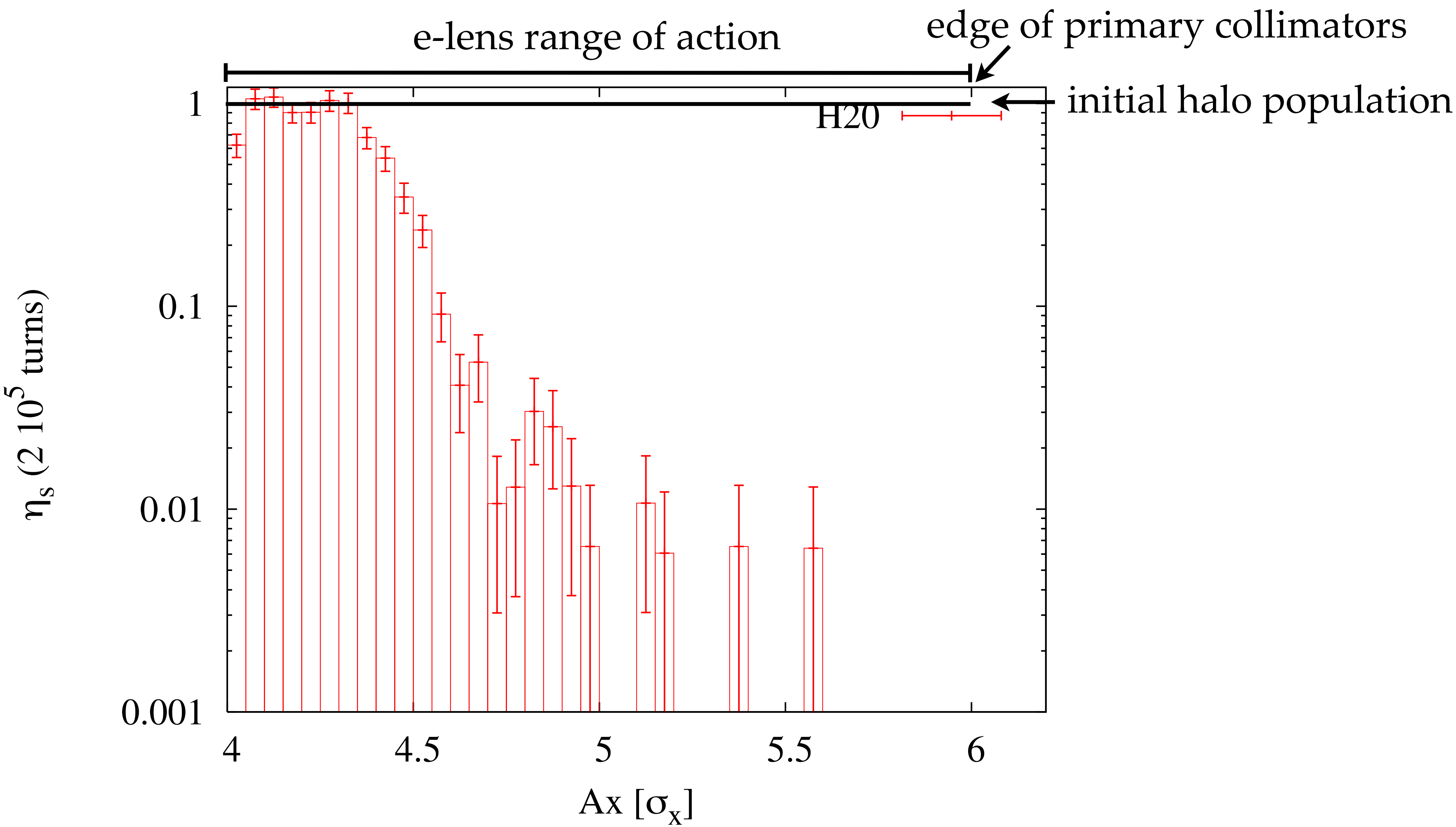
Results of numerical simulations

- Flexibility of high-voltage modulator enables different modes of operation:
  - *continuous*: same electron current every turn
    - *Most of Tevatron experiments done in this mode*
  - *resonant*: current modulated to excite betatron oscillations (sinusoidal or skipping turns)
    - *Used for clearing abort gap in Tevatron*
  - *stochastic*: random on/off, or constant with random component
- **Observable effects** in time scales of seconds/minutes
- **Smooth scraping** with electron pulsed every turn
- **Enhanced removal rates** with resonant or stochastic modes
  - Resonant mode depends on details of tune distribution
  - Stochastic mode is very robust
- **No adverse effects on core**
  - in continuous mode
  - in resonant mode in ideal case
  - effect of imperfections (profile asymmetries, injection/extraction bends) under study

Previtali et al., FERMILAB-TM-2560-APC (2013)

Example of simulated halo scraping (SixTrack, LHC lattice)

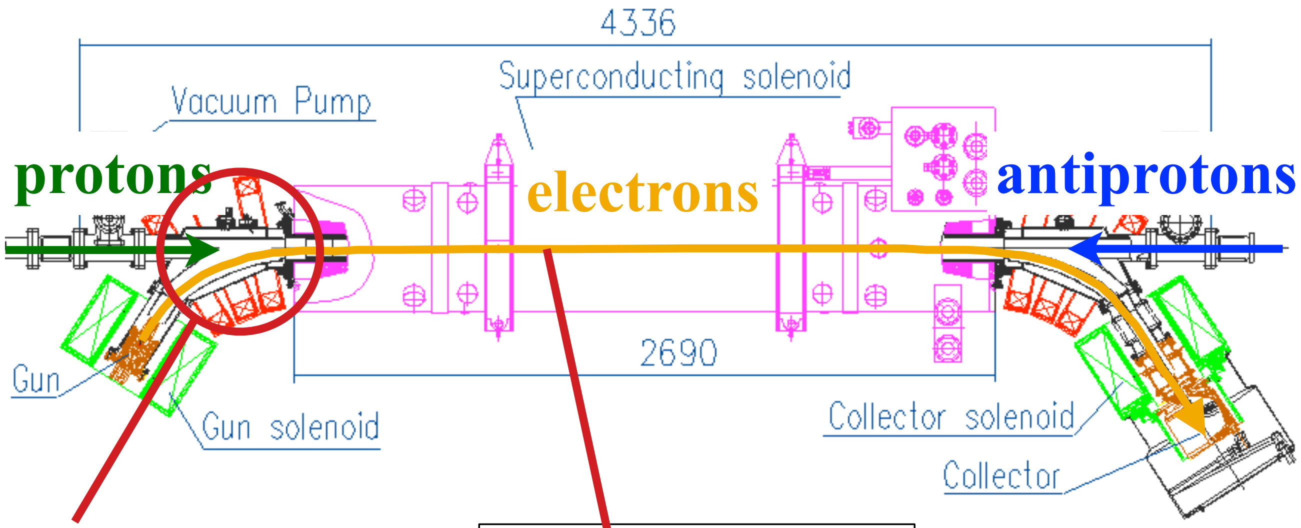
Residual halo population vs. betatron amplitude after 18 s of resonant scraping



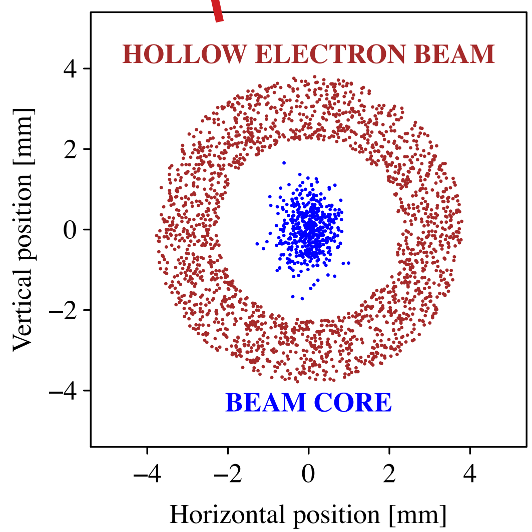
Previtali et al., FERMILAB-TM-2560-APC (2013)

Effect of asymmetries in electron distribution on circulating beam

No adverse effects were observed at the Tevatron in continuous operation, but application to the LHC may require higher beam currents and different pulsing patterns. We studied two sources of asymmetry:



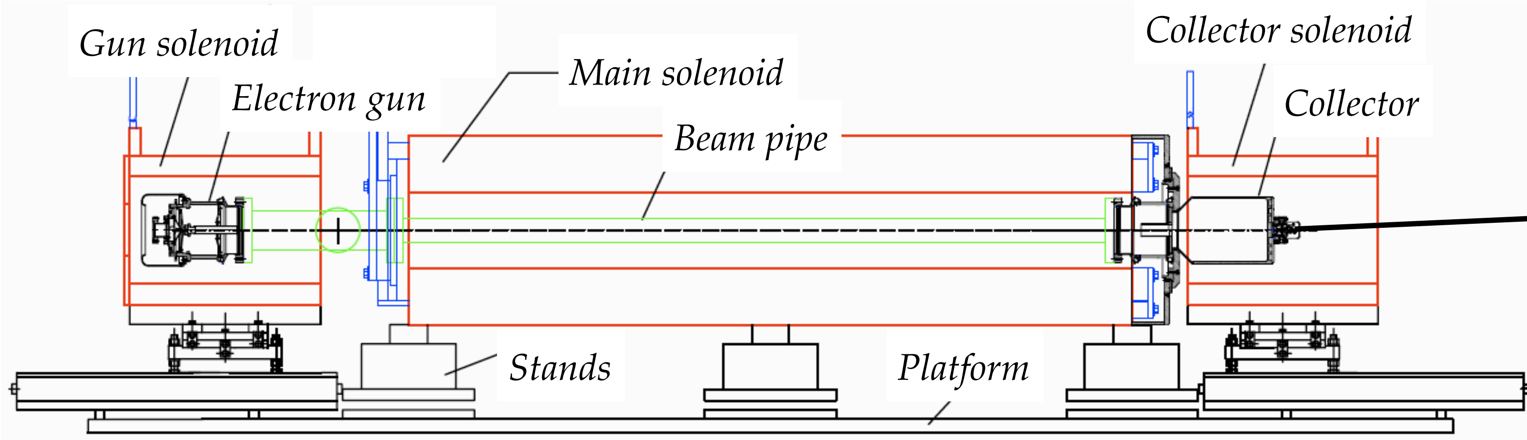
1. bends for injection/extraction



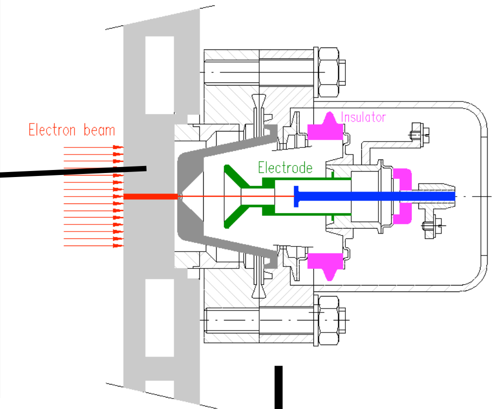
2. azimuthal asymmetries in overlap region

Azimuthal asymmetries in overlap region from measured profiles

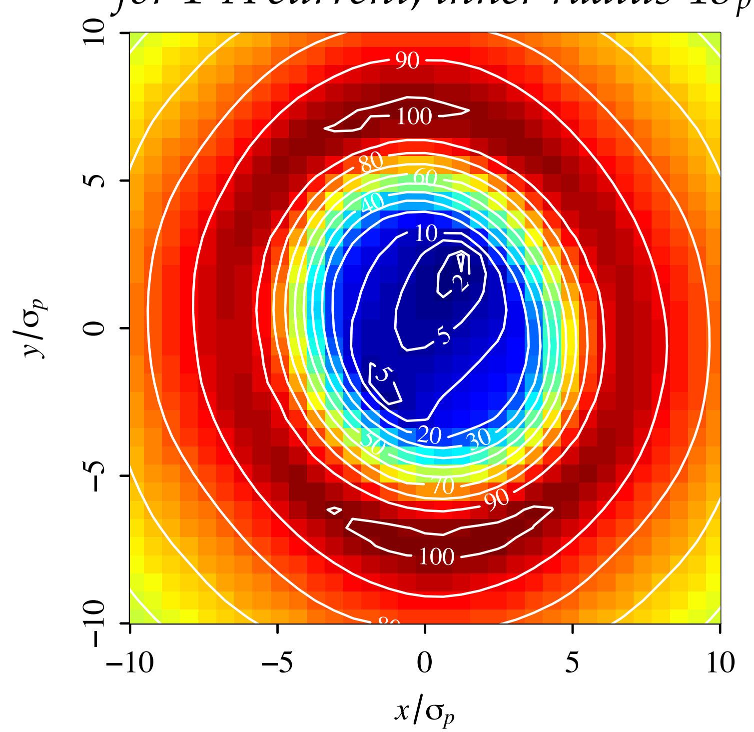
Fermilab electron-lens test stand



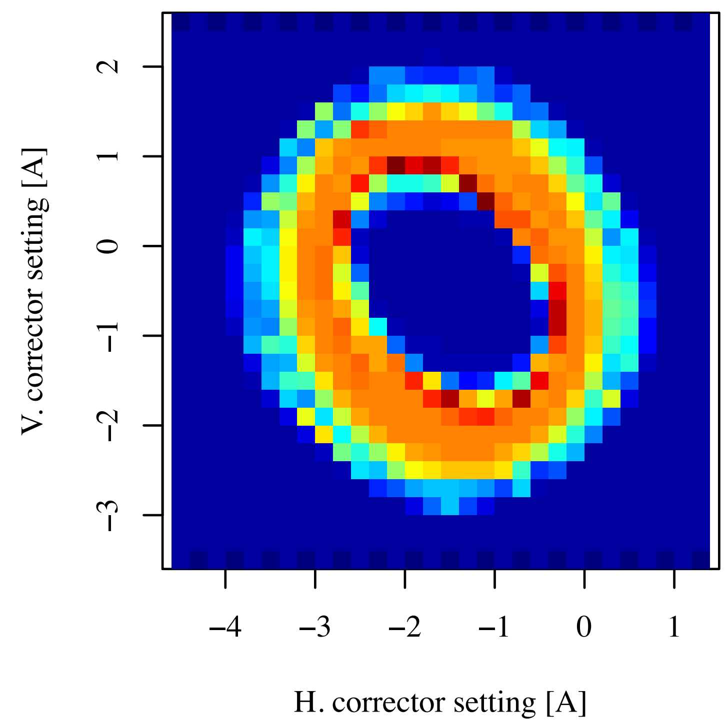
Pinhole for current-density measurements



Calculated electric field [kV/m] for 1-A current, inner radius $4\sigma_p$



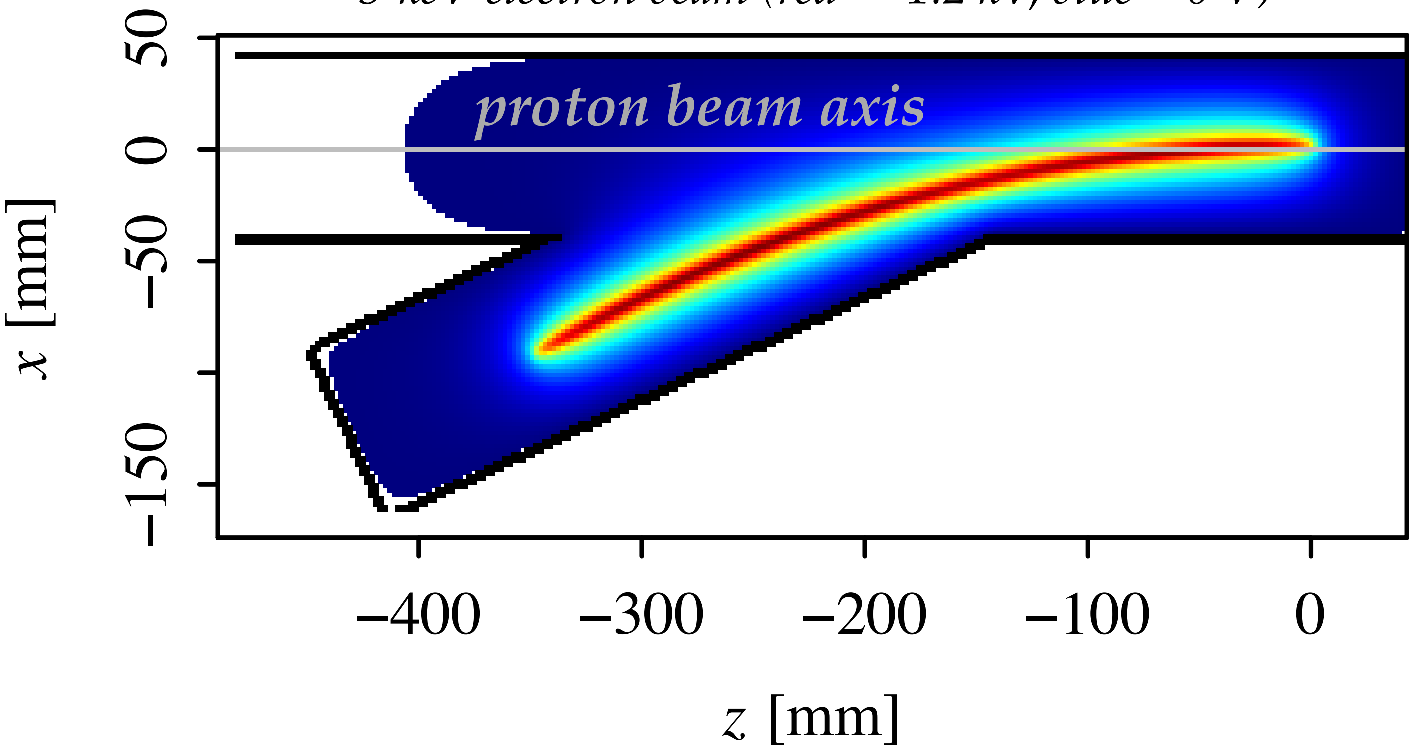
Example of measured profile



Kick maps from injection and extraction bends: simplified approach

3D calculation of electric fields generated by a static, hollow charge distribution inside cylindrical beam pipes using Warp particle-in-cell code

Electrostatic potential on the plane of the bend for 1 A, 5-keV electron beam (red = -1.2 kV, blue = 0 V)



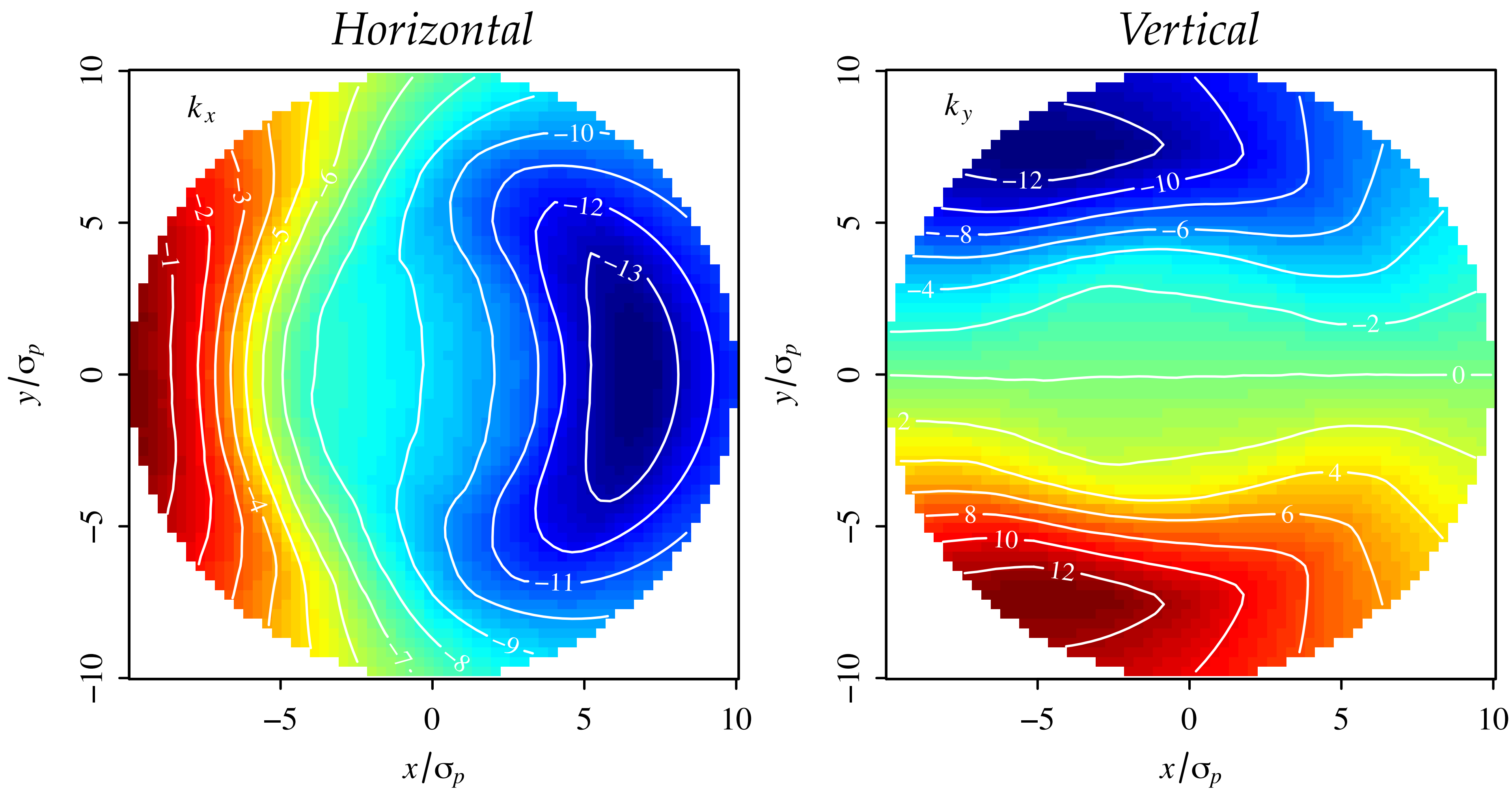
Kick maps are calculated by integrating electric fields over straight proton trajectories

$$k_{x,y} \equiv \int_{z_1}^{z_2} E_{x,y}(x,y,z)\, dz$$

Stancari, FERMILAB-FN-0972-APC (2013)

Kick maps from injection and extraction bends

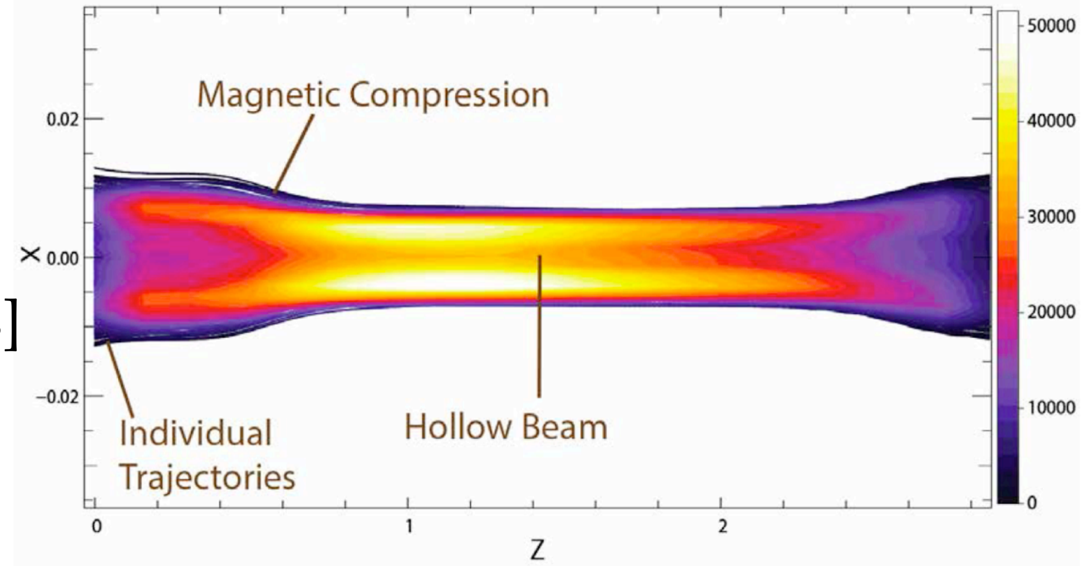
Integrated fields ('kicks') [kV] vs. transverse proton position



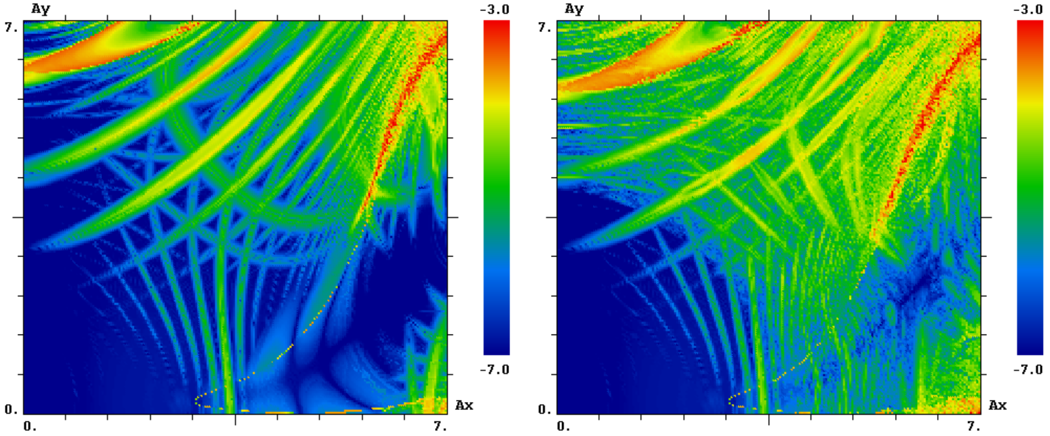
For 7-TeV protons, 10 kV ⇒ 1.4 nrad

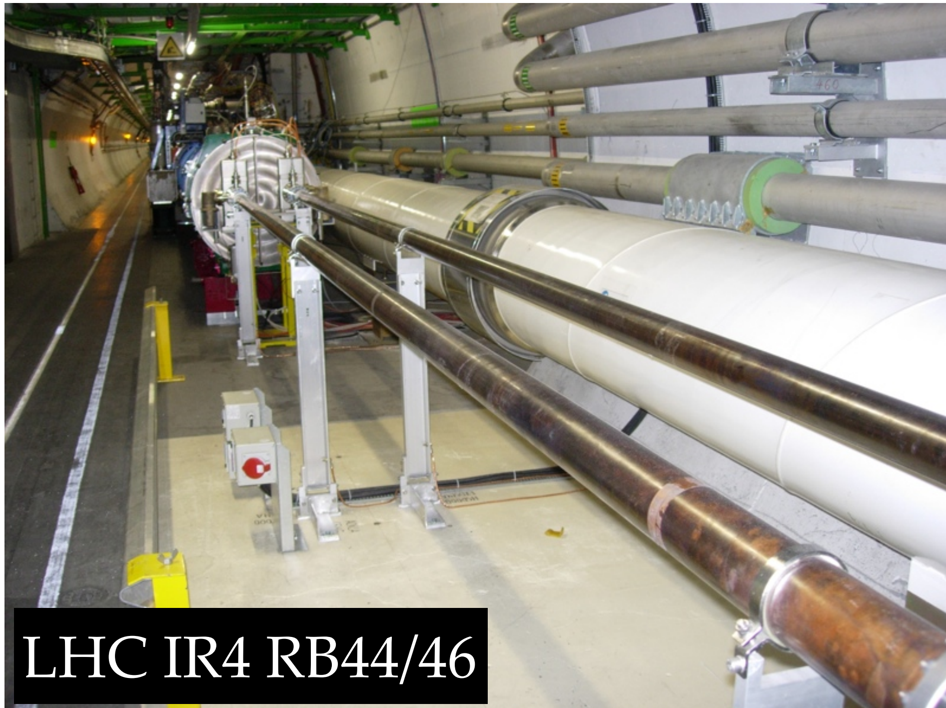
Ongoing simulation work

3D simulation of electron beam propagation in electron lens with Warp particle-in-cell code [V. Moens]

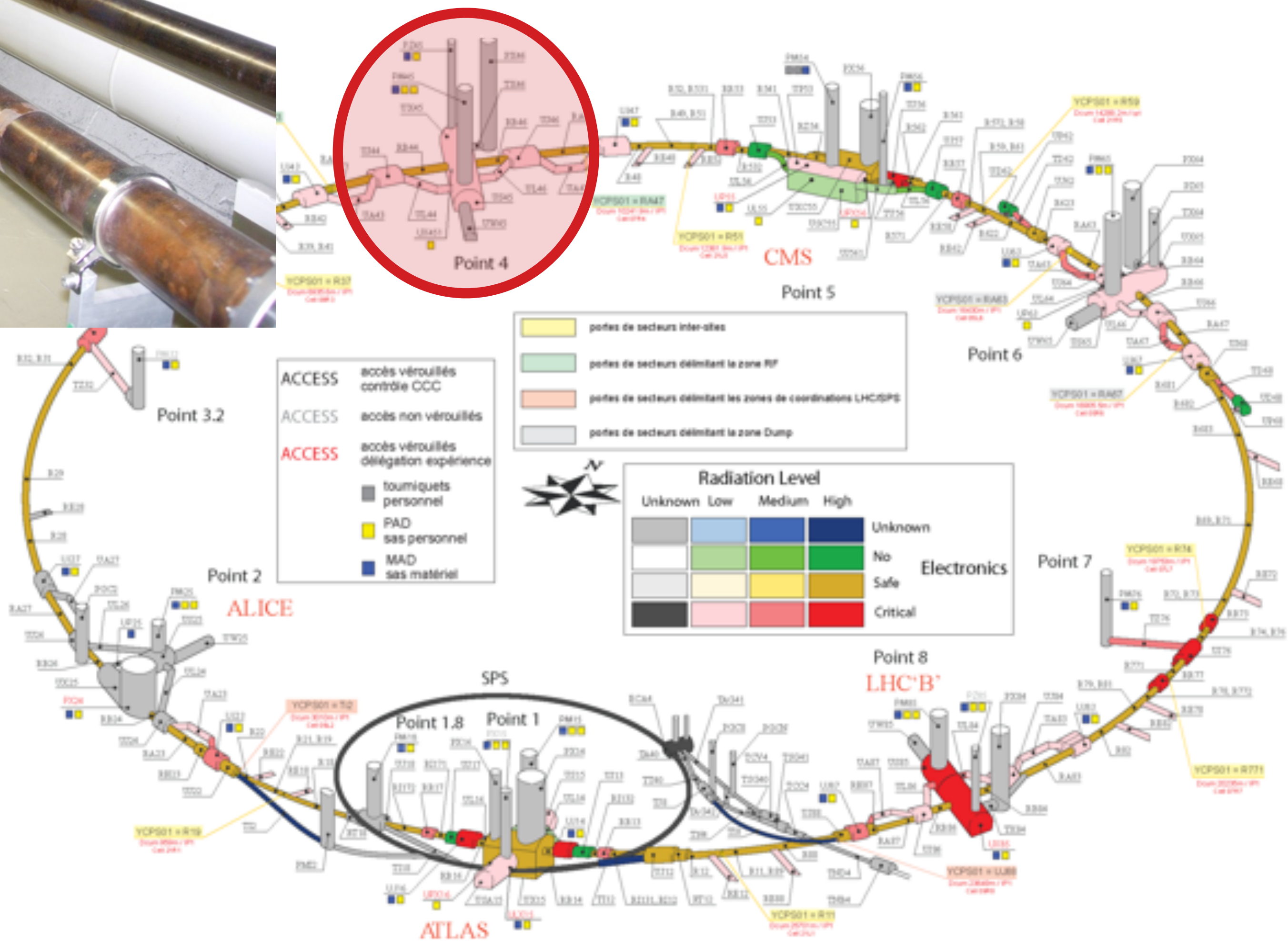


Inclusion of kick maps in Lifetrac tracking code for evaluation of core lifetimes, emittance growth rates, and frequency maps in continuous and pulsed electron-lens operation [A. Valishev]





Upstream or downstream of rf cavities



Some aspects of LHC integration

- **Cryogenics**
  - dominates installation time: ~3 months; “long” shutdown needed
  - electron lenses can be treated as stand-alone magnets
  - may take advantage of dedicated rf refrigerator (if confirmed)

- Because of the different **bunch structure** (25 ns or 50 ns vs. 396 ns), preliminary **impedance** studies suggest that
  - modifications of Tevatron vacuum chamber and electrode designs may be required for longitudinal fields
  - transverse impedance is acceptable

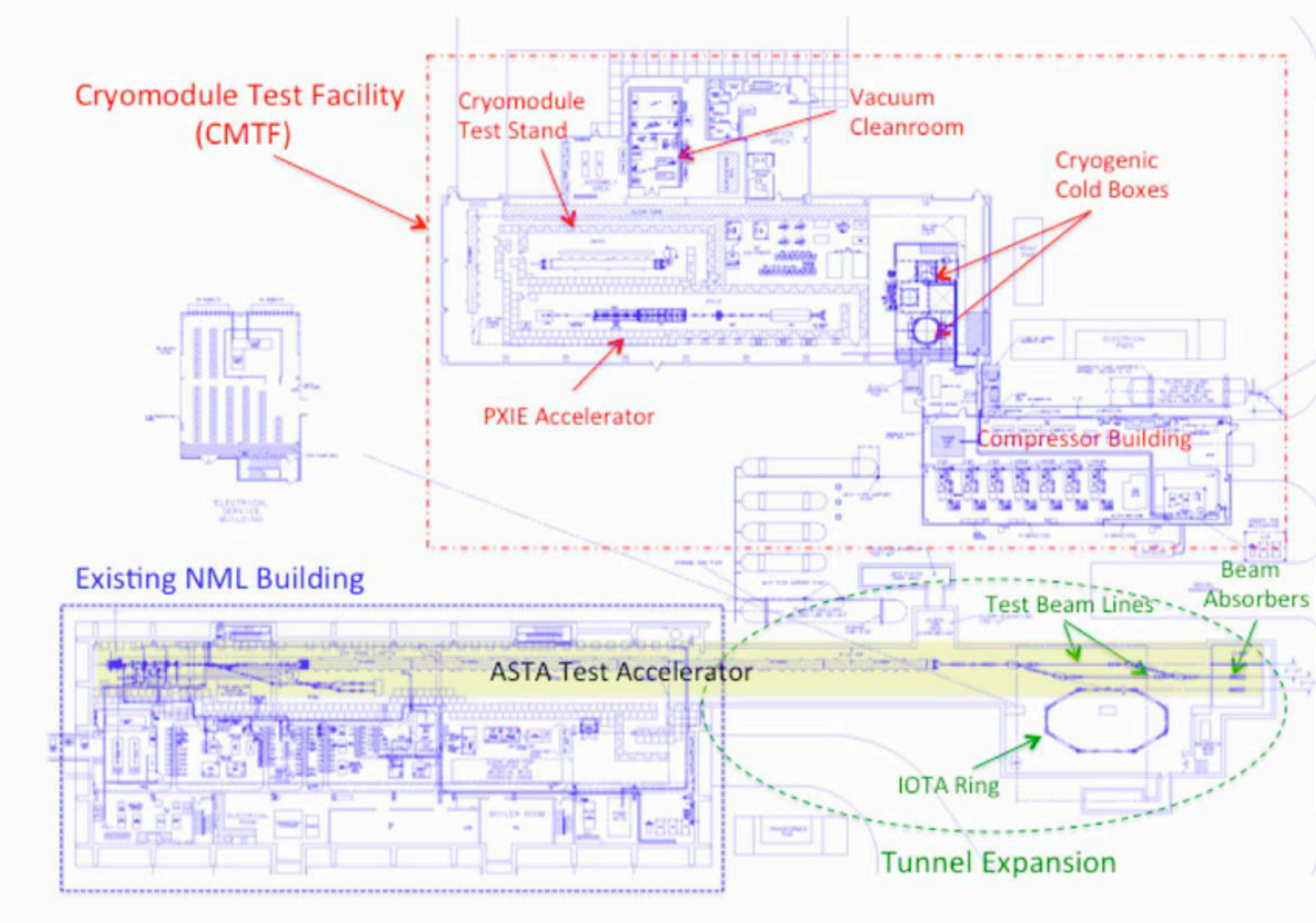
- Introduction
- Electron lenses and their applications
- Hollow electron beam collimation
- **New accelerator research facilities at Fermilab**
- Conclusions

The new beam physics research center at Fermilab

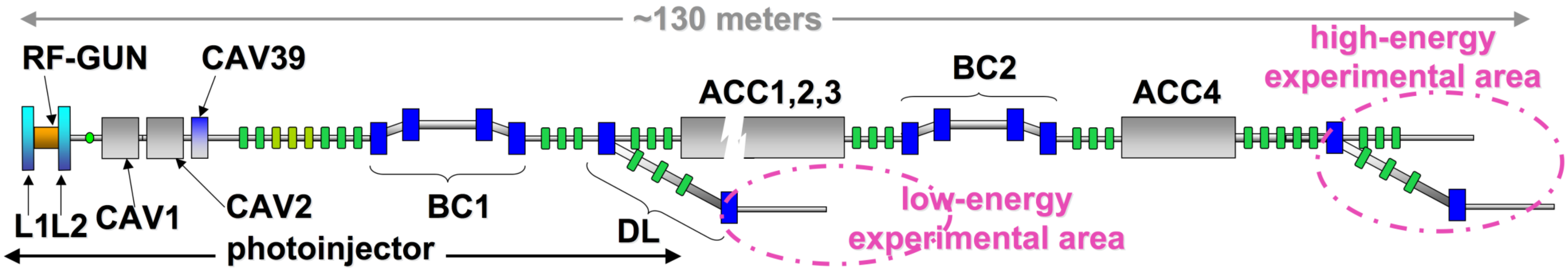
ASTA: Advanced Superconducting Test Accelerator

http://asta.fnal.gov

Floor plan of the facility



Photoinjector and electron linac



40 MeV – 1 GeV e^- beams

0.02 – 3.2 nC/bunch

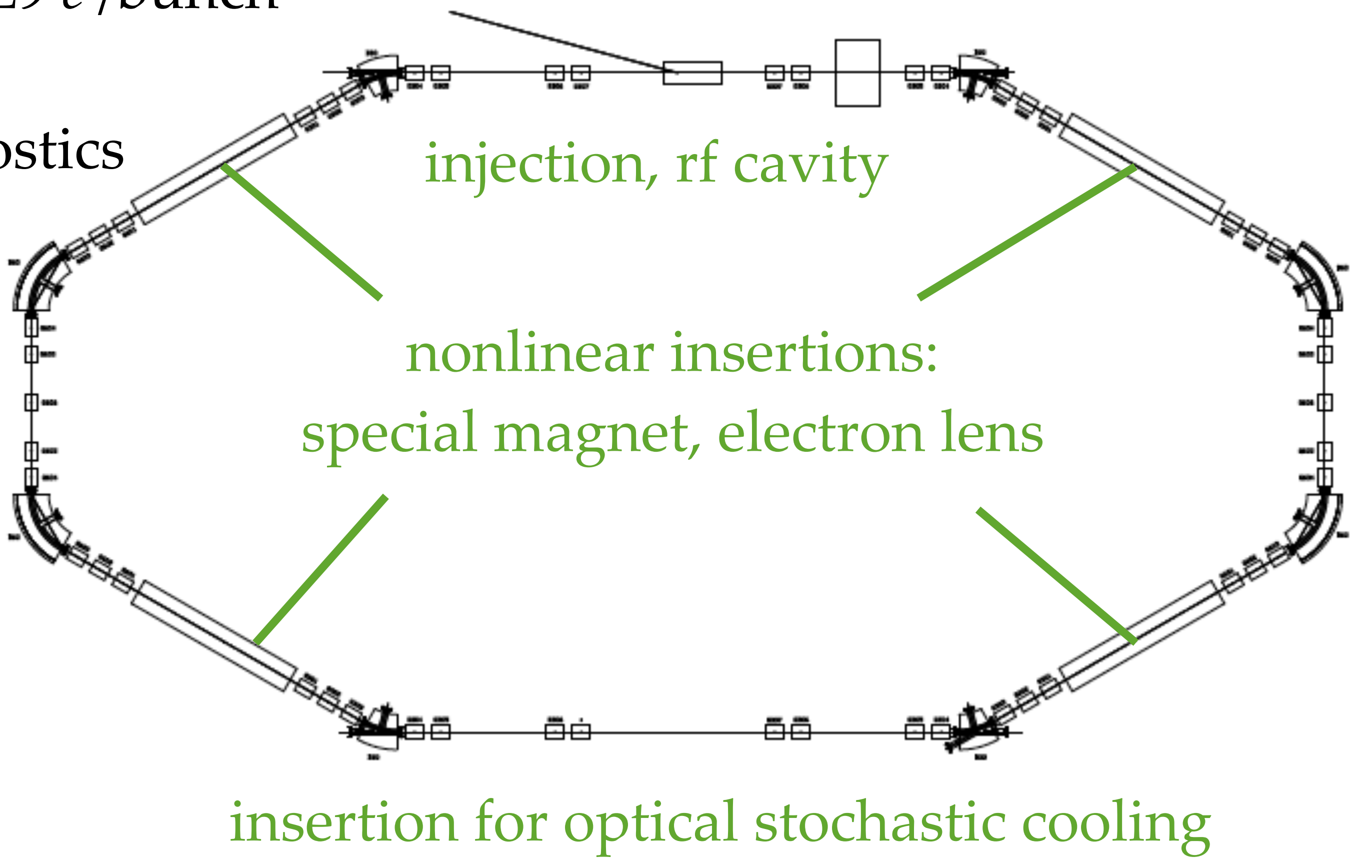
1 – 3000 bunches in 1-ms trains at 5 Hz

high brightness and stability

Integrable Optics Test Accelerator (IOTA)

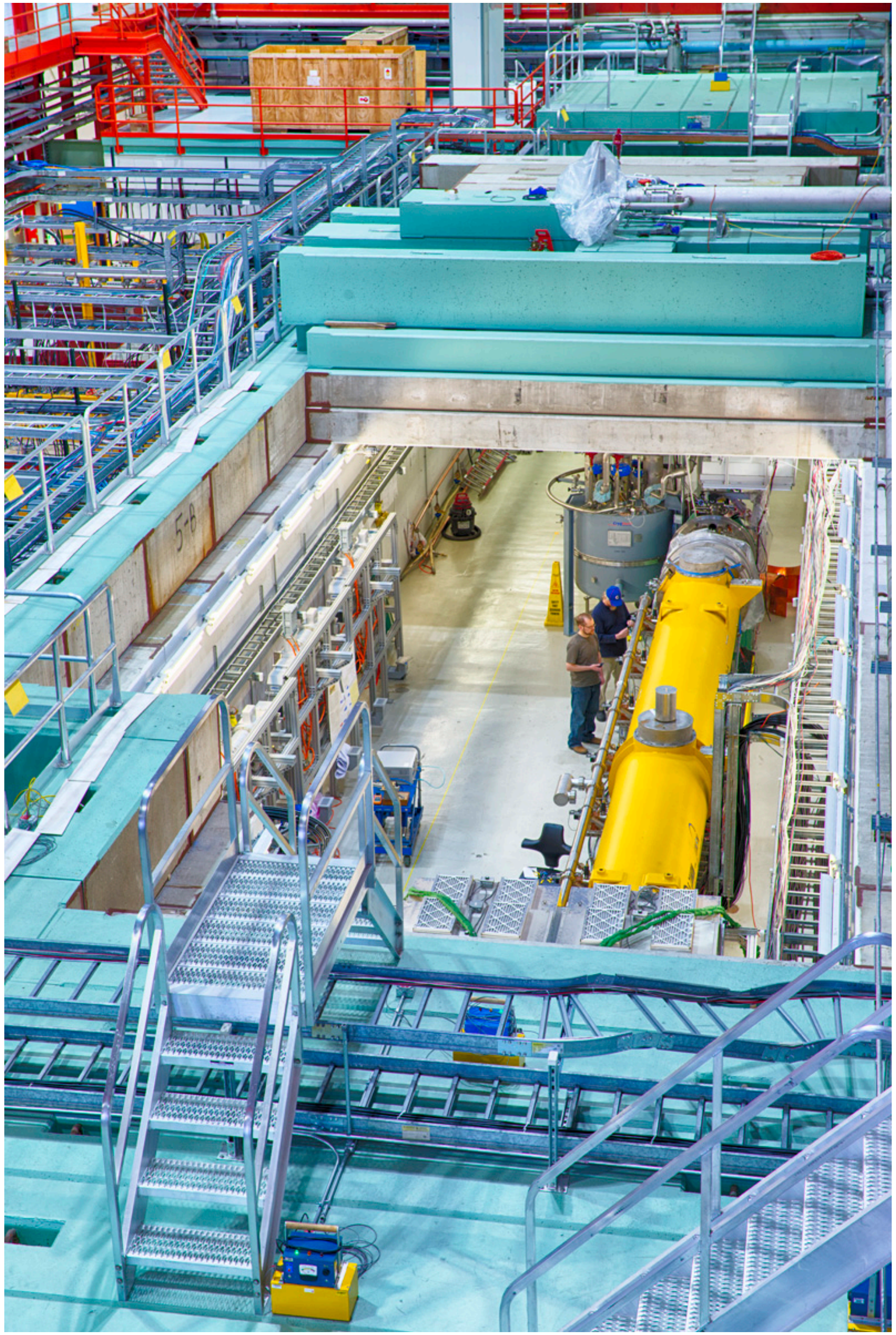
Is it possible to design a highly nonlinear lattice with large dynamic aperture and a correspondingly wide tune spread to avoid instabilities (Landau damping)?

50 – 150 MeV e^- beams; 1E9 e^-/bunch
40 m circumference
flexible lattice and diagnostics

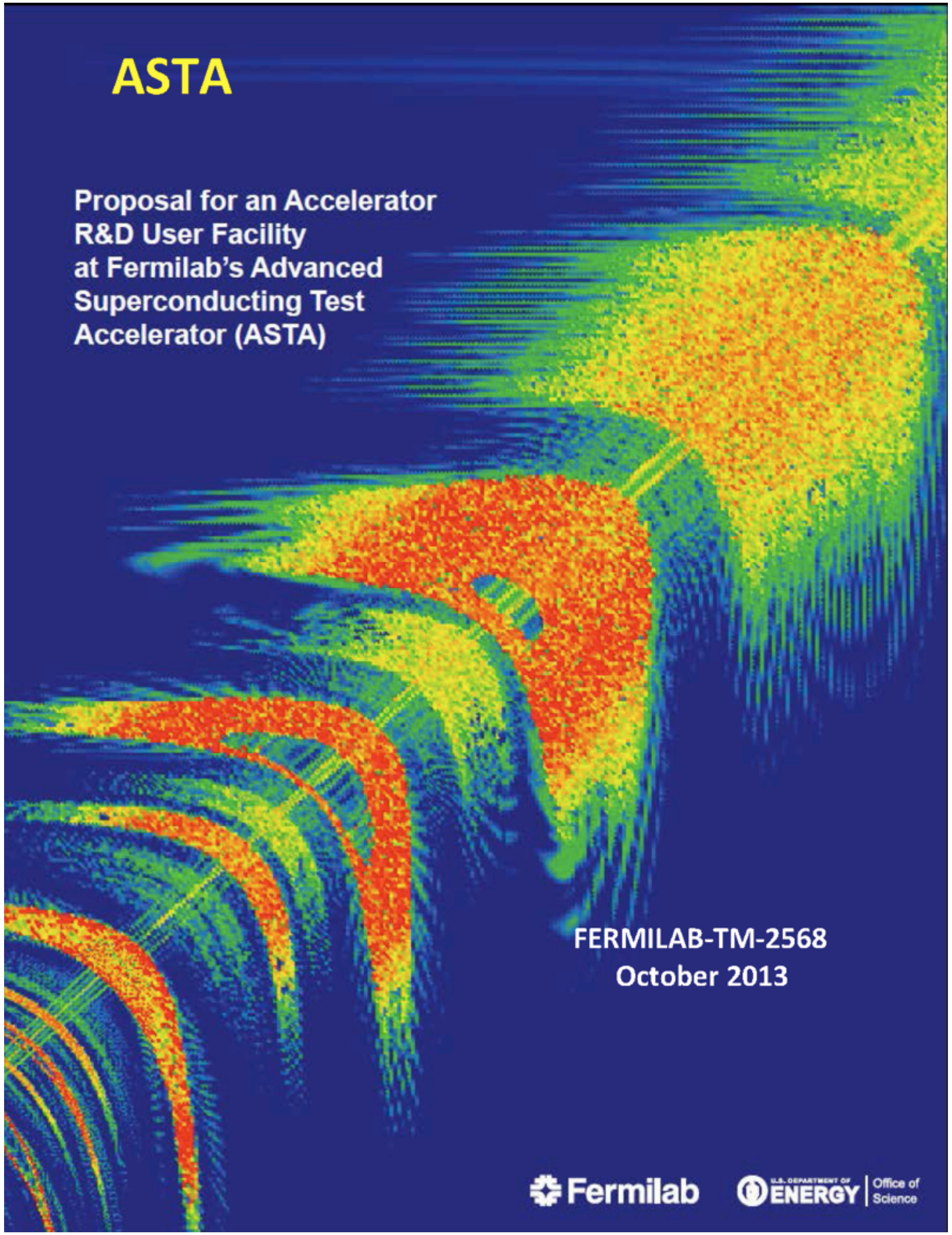


Danilov and Nagaitsev, Phys. Rev. ST Accel. Beams **13**, 084002 (2010)
Valishev, Nagaitsev, Danilov, and Shatilov, IPAC12 (2012)

Interior of the facility



Research proposals



Summary and conclusions

- **Electron lenses** are a mature technique for beam manipulation in circular machines.
- A novel concept for **collimation** of high-power hadron beams with **hollow electron lenses** was developed at the Fermilab Tevatron collider.
- A conceptual design of hollow electron beam scraper is being proposed for the Large Hadron Collider upgrades.
- Fermilab is initiating a new program of accelerator research with **high-brightness electron beams** at the **Advanced Superconducting Test Accelerator**.
- **Collaborations** and **ideas** are always welcome.

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Thank you for your attention!